

A novel method for detecting light source for digital images forensic

A.K. ROY, S.K. MITRA*, and R. AGRAWAL

Dhirubhai Ambani Institute of Information and Communication Technology, Gandhinagar,
Gujarat 382007, India

Manipulation in image has been in practice since centuries. These manipulated images are intended to alter facts – facts of ethics, morality, politics, sex, celebrity or chaos. Image forensic science is used to detect these manipulations in a digital image. There are several standard ways to analyze an image for manipulation. Each one has some limitation. Also very rarely any method tried to capitalize on the way image was taken by the camera. We propose a new method that is based on light and its shade as light and shade are the fundamental input resources that may carry all the information of the image. The proposed method measures the direction of light source and uses the light based technique for identification of any intentional partial manipulation in the said digital image. The method is tested for known manipulated images to correctly identify the light sources. The light source of an image is measured in terms of angle. The experimental results show the robustness of the methodology.

Keywords: image forensics, manipulation, least square approximation, surface normals, decorrelation, noise filter.

1. Introduction

Human beings think in images. Communicating through images has been more ancient than that through dialects. Images are the oldest form of recording data whether it is on wall, paper, canvas, photographic plate, film, or any digital media. The enormous progress in digital technology and the complete ignorance of its indirect social consequences led to several major sociological impacts. One of them includes tampering with this oldest form of mode of communication. Image tampering may sometimes interchangeably be stated as image forgery or image manipulation. It is about making some change in the image that is easily possible by using suitable software such as Photoshop or MS Paint.

The present competitive and materialistic world has unlimited examples of the image forgeries. An image can create, convey or change the human perception about someone or something irrespective of its genuine possibility, because it is a form of evidence or a record. This uncanny importance of an image may tempt one to manipulate it for some intentional gain. The advent of digital photography and design software has been a major cause for the unlimited breaches of image originality. The one of the earliest reported case of image forgery was in 1860 that was a composite of U.S. President Abraham Lincoln's head and the southern politician John Calhoun's body [1]. Today image manipulation techniques have been in use by a political party [2–3], social networking portals [4], scientific journals [5–6] or in photojournalism [7] etc.

Images are very finely knitted all over in our lives. Therefore the tampering of images causes in numerous real life problems ranging from unethical politics, photo-journalism, fake art and paintings, character assassination, winning photography competitions, misleading advertisements, fake news, tweaking with cell and gel images and celebrity magazine covers. As the problems created by the image manipulation affect almost all walks of the society, a solution for identifying such manipulations is also desired in a broader perspective. Image detection is a tool to verify if an image is original and provide us with some technically verifiable authentication to accept or reject such claims. Many questions on genuineness could pop up, which cannot be challenged unless otherwise proven based on some technique of image forensics.

There are many techniques of image forensic to establish if the image is original. In Sect. 2 we will quickly review those techniques and discuss their limitations. No technique is perfect. The best way to find some manipulation in an image has still been through some experienced visual judgment. We looked into the recording of an image from the very fundamental aspect. It is the object, the photographer and the device that know the reality of the image. The object may not be human being all the time. The device, that is camera, is a silent entity of the complete process. So, if the photographer or a person related to the photographer has some ill intention of tampering with the image, nobody else can establish with certainty that the image is original or fake. But our understanding of recording an image stresses on the fact that if it is an outdoor photography, the direction of light and the formation of the shadow thereby – are two major components that record the originality of the image in

* e-mail: suman_mitra@daiict.ac.in

the image itself. Keeping this in mind, in this paper we propose a method that measures the direction of light source and uses the light based technique for identification of any intentional manipulation in the image. Our proposal is discussed in Sect. 3 and the algorithm that does the forensic is elaborated in Sect. 4 followed by the result discussion and conclusion in Sects. 5 and 6, respectively.

2. Overview of image forensic techniques

Image forensics, watermarking, photomontage are some of the standard techniques to find if an image is manipulated. A manipulated image is usually called a composite photograph which is produced by pasting an object or selected region from one image onto another image. In case of composition of photographs, it is extremely difficult to match the lighting effects due to directional lighting when a composite image is created. The light source direction differences may not be too significant to be detected by the human eyes. In some cases, due to colour contrasts, the image might look sceptical even being the original.

Since light is an inseparable factor of an image, there are several techniques of dealing with fake or manipulated images in the literature or image forensic science based on light source direction, light intensity or shadow [8–19]. In an image, the brightness of a certain region of an image varies with the variations in the shape of the real object [8]. Such brightness variations provide the shading to the image. The concave and convex features of the surface can be known in presence of cast shadows that provide illumination direction [9]. The technique of specular highlights in eye is useful when the eyes are large in images [10]. It has been indicated in Ref. 11 that highlights are the reflection models that can be used for estimation. As the eyes become smaller, the selection of eyes as elliptical approximation would lead to an inaccurate estimation of the light direction. The constraints can be imposed from the eyelid occlusion also. All the light based techniques are always constrained by the assumption that the adversary has not been extremely careful and it is unable to create or simulate the same lighting conditions for two or more objects. The method of specular highlights fails to reveal any inconsistency in some cases like [12].

Another method of estimating light source direction from single image works out with heuristic picking of potential occluding contours [13]. The light source direction is estimated for each contour using shading model. Most of the techniques to estimate manipulation use standard or pre-defined geometric shapes. In case of objects of irregular geometric form, segmentation and the height information can be used for the estimation of light source direction [14]. The shading technique has an assumption that depth range is small compared with the distance of the scene from the viewer [15]. The limitation of this technique is the risk of loosing dimensional information while converting into grey scale and quantizing at a later stage.

Robust match techniques can be used for the detection of ‘copy and move’ forgeries [16,17]. Pattern recognition is one such tool for detecting image manipulation as shown in Fig. 1. These techniques are though successful, a lot of human interpretation and judgment are required for the analysis of the results. In some robust match techniques it is assumed that probability of occurrence of two similar regions on an image is very low [18].

Inconsistency in lighting environment technique can be used to detect engineered images [19]. Inconsistency in light source direction on various parts of the image may expose misrepresentation of truth in a photograph. This technique by Farid can be used to establish the fact for many such images [20]. Here, again human interpretation of image plays very important role. Segmentation can be used to detect forgery by deletion, copy and paste and the healing tool of Photoshop [21]. While deletion can be detected using segmentation based on intensity, copy and paste is detected by duplication based segmentation. Texture based segmentation is used for healing tool forgery. However, such techniques are vulnerable to a host of countermeasures to hide traces of tampering.

Shadow inconsistencies in the Moon expedition images have been since long a matter of controversial debate [22]. The shadow is very powerful forensics tool as it tells about

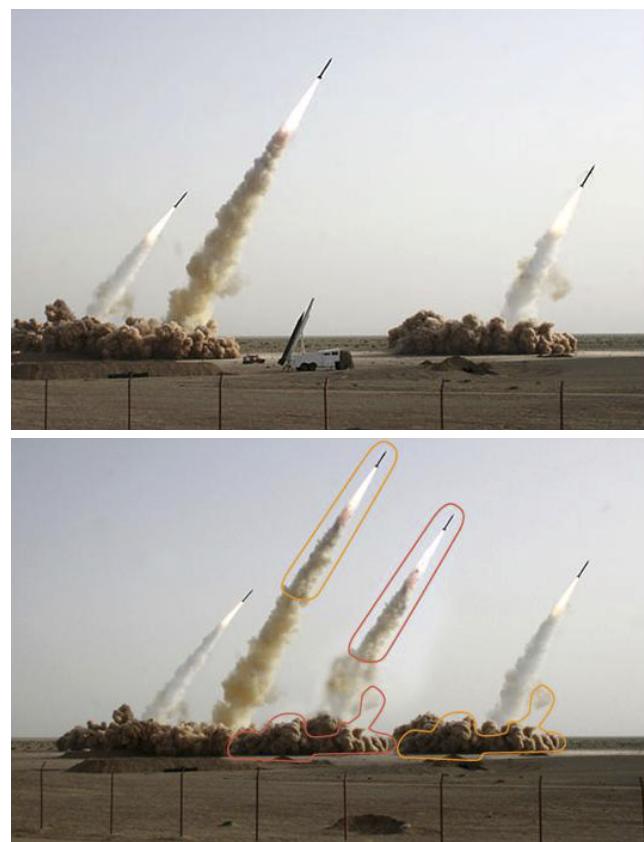


Fig. 1. Misrepresentation of reality by unethical photojournalism. The photograph of Iranian missile test (up) is a fake image hiding the fact – that is presence of 4th missile as shown in original image (down) [15].

the light source. Hence, it speaks about the lighting inconsistency in the image. It reveals the geometry of the subjects and their relative distances. The shadow volumes can be used to define light sources as the shadow volumes depend only on the light and object position [11]. The reductions have been reported where the shadow can be used to reduce the light zone and the illumination direction [23]. If the complete object and its shadow is present in the image, the light direction can be geometrically measured by joining the corresponding points.

3. New proposal

Almost all methods described above have some limitations. The image manipulation has been developed in such perfection that even after blowing up of images, the stitching cannot be identified. Our proposal in such cases aims at identifying the manipulation by the difference in angle of incidence of light source which may not be possible by normal human judgment.

Conceptually it is understood that an image is produced if there is a light source. Let us consider that the image is taken in an outdoor day light condition assuming that there is a single light source for one particular image that has been shot. Therefore we may define that an original image is one in which light is incident on all objects at a fixed common angle. If someone manipulates this original image by inserting some object from another image source and generates a new image claiming that it is the original one, then the angle of incidence of light on this inserted object will most probably be different from the former original image. If we can measure the angles of incidence of the light from the source of different objects of an image in question, we can confidently say whether the latter image is original or fake. This is the basic principle of our new proposal which is described hereunder.

The measurement of the angle of incidence of light has been discussed in the literature by techniques based on specular highlights [19], shadows [23] or shading [24]. Each technique has its own advantages and disadvantages. Specular highlights require a shiny reflective surface. In human body, as stated before, such surface can be found in eyes that might be blocked by eyelids or eyes could be closed. So, this technique might not be very useful when manipulation is done in images of human beings. Shadow technique can be used for measuring angle of incidence in presence of complete object and its complete shadow in the image, which is rarely available in an image. On the other hand, shading technique has limitations because of very sharp curvatures on object surfaces that may give wrong results while estimating normal to the surface. Apart from this, error might also come in because of discrete nature of intensity pattern of the image due to digitization (mach bands). However, very sharp curvatures are usually found only near the boundaries of the object. Therefore a small region from the object can be used to measure angle of incidence carefully ignoring the boundaries of the object in the image. This is

exactly what we are aiming at while proposing the new method for image forensic.

The light source direction must be the same for all objects in an image for the image to be original if light is coming from a point source. In this proposed technique we calculate the direction of the light source by measuring the angle. The surface is considered to be Lambertian for ensuring that the brightness is constant from all viewing angles. A fixed block from the object area is selected where a sharp transition from illumination to shadow is taking place but away from the boundary. We keep the selection manual as this empowers to select region according to the skepticisms – that is the manipulation consists of adding second object in presence of first or by replacing part of an object by similar part of another object (such as replacing the head).

The measurement of the angle of incidence requires knowledge about the surface structure from which surface normal can be calculated. The selected region, however, contains intensity flow along with the structural information. Further, it also possibly contains noise due to various imperfections in the optics of the camera and the subsequent digitization process. Our approach considers the intensity captured by the camera for deriving the structural information. Thus, we require a uniform intensity flow. The more accurate surface feature extraction requires removal of the noise which can be realized using certain filters. The structural profile can be segregated from the intensity profile using high contrast and exaggerated curvatures. This makes our technique distinct from the traditional methods where surface information requires multiple images [23] or objects of predefined geometrical shape [25], usually spherical, which is not possible when the image source and the object are not known. The noise of the image is the different pixels containing sudden distinct intensity as compared to the neighbours which can produce errors in the estimation of angle of incidence of light source. Such noise is reduced for deriving the better surface features using the Max filter [8]. It is a type of order statistics filter where the centre pixel of mask is replaced by the maximum pixel value present within the region of mask [8]. Note that this module in the present algorithm could be made optional in case one is dealing with images which are of good perceptible quality. Max filter completes our requirements with significantly low response time against several neighbourhood operating filters.

After applying filter we use de-correlation stretch [8]. De-correlation stretching enhances the colour separation of an image with significant bend-band correlation. The exaggerated colours improve visual interpretation and make feature discrimination easier. This de-correlation allows enhancing the colour separation peaks on the block terrain. The colour values are mapped to a wider range and to equalize the band variance. Such enhancement provides the enhanced visualization for the intensity profile. The de-correlation stretched images contain all the three RGB bands. In our analysis we use only red band values that contain the enhanced values. A series of experiments on the images provides valid reasons for considering red band values as intensity

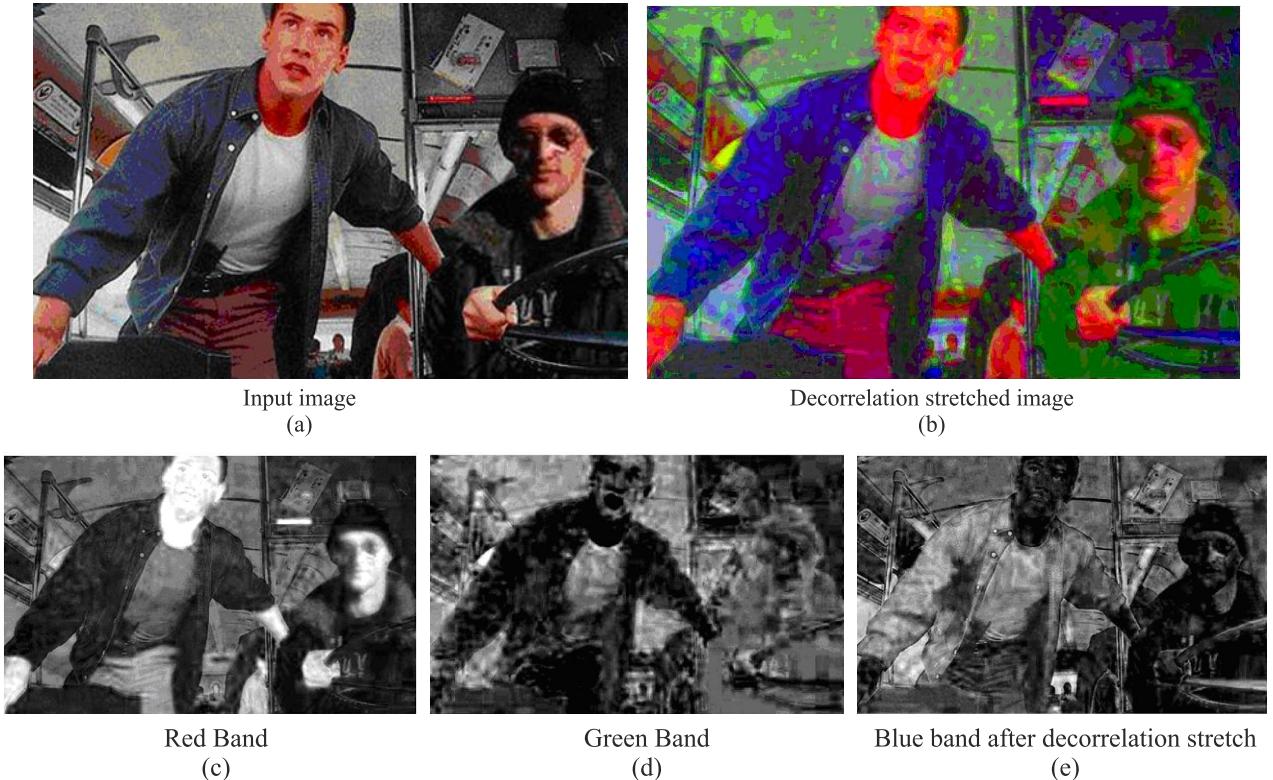


Fig. 2. Comparison between RGB bands of images after decorrelation stretch. The red band clearly contains the best intensity profile.

for our further calculations. The de-correlation stretched red band image clearly completes our requirements by providing an appropriate intensity profile. The images below show the original image de-correlation stretched image, and R, G & B bands in sequence.

The images after de-correlation stretch can easily be inferred to present the shading (intensity) profile through the red band values as in Fig. 2(c), however, such information is lost in case with green, as shown in Fig. 2(d), or in blue, as in Fig. 2(e), bands. Therefore we use only red band (scale) values as intensity profile values in our analysis of an image.

We now proceed for finding structural profile information from the initially selected block. We use only the red scale values for the structural profile also. Adaptive histogram equalization uses histogram equalization on various small sized sub-blocks [8]. The processed sub-blocks are then interpolated to give back the image. Such process, also called localized or windowed histogram equalization, stretches the red band values over the wide range. It reduces the errors caused by abrupt discontinuities and mach bands produced due to digitization process which are major error producing reasons for estimation of surface structure. The contrast stretched image thus acquired contains the red band gradients that can be used as the z-direction gradients on the surface of the objects. The image in Fig. 3(d) clearly represents the enhanced structural features especially of the regions selected under the constraints discussed above for the manual selection of the block. Normals and the intensity profile of the region can be used for the calculation of angle of incidence of light source.

The derived structural profile can be exploited for estimating the normals at various points of the region. The normal at any surface can be geometrically found if any three points are given. Considering the small sub-block with not high varying texture allows the use of the set of three points in the neighbourhood of a point to acquire the surface normal at that point. We followed the same concept and used sets of three points (neighbourhood) as vertices of a triangle around each point of interest and calculated the surface normal vector.

Under the assumption that surface of objects in the image is Lambertian, the intensity I at a point of the image can be calculated [26,27] by the following equation

$$I = k(\vec{n}\vec{l}) + a \quad (1)$$

where $\vec{n} = (n_x, n_y, n_z)^T$ is the surface normal at that point, $\vec{l} = (l_x, l_y, l_z)^T$ is the direction to the light source. We have assumed the parameter ' k ' as constant reflectance of the surface. The parameter ' a ' represents the contribution of the ambient illumination. The assumption of Lambertian surface is required as we are interested in non shiny surface with suppressed specular components for which Eq. (1) gives good approximation.

The assumption that the light is reflected equally in all directions by the surface (Lambertian surface) and the local estimation for a region might introduce error in calculation of angle of incidence. However, in presence of large number of points, the error can be reduced by finding best fit model for the above system. This is what we aimed at initially,

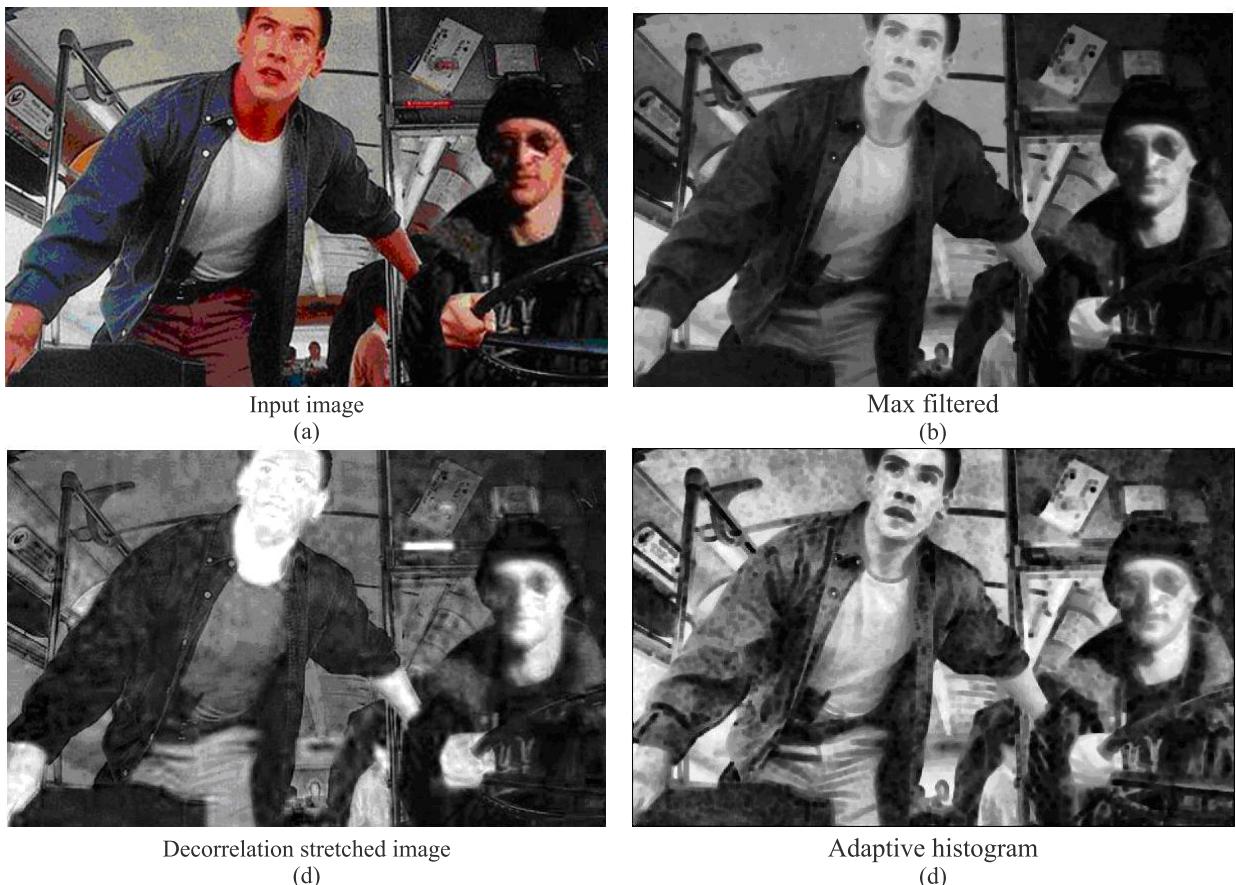


Fig. 3. Images at different stages of the process.

approximating a best fit angle of light incidence from a source on an object using a small region to represent object that makes it feasible in case when the images may not contain the whole object.

4. Detailed process

The dataset used consists of:

- original images with two or more objects for verification of consistency in light source direction,
- original produced in the laboratory for the verification of the direction of estimated light source. Canon Power-Shot SD770 was used for capturing the images,
- simulated fake images for the verification of inconsistency in light source direction, standard fake images available over the Internet.

The original images with two or more objects are required for verification of results. The angles of incidence on both or all the objects in the image must be the same for authentication of the image. As the images are expected to be real, the results should always provide the same angles. The images from *flickr* and personal collection are used to verify the above fact.

The originals in the laboratory are produced by taking photographs of objects under simulated environment similar to one taken outside on a clear sunny day. A white halogen lamp at a distance of 10 meters from the centre of the floor is

used as a single and only light source in the laboratory. Considering the long distance between the source and the object, the light source can be considered as a point source. The lamp can be rotated to angles 30° , 45° , 60° , 70° , 75° , 80° , and 90° , taking 0° along the horizontal plane on which the object rests. The distance of the light source is kept fixed for all the angles. The pictures are shot from a stationary positioned camera for all angles without camera flash for keeping the shadows within the image. Objects of different shapes are used to verify that the technique we have discussed does not have constraints for the shape. The image obtained by fixed angles allows us to verify the angle of incidence of light ray estimated by our technique. The images are captured to include the whole object and its complete shadow. The shadows allow easy direction reductions and in case of single point light source they can help in detection of angle of light source direction. These angles are used for the verification of accuracy of the estimated angle of incidence using our proposal.

The original images produced in laboratory are used to create manipulated images (fake images) by copying an object from one image and pasting in another. The manufactured composite images of this nature are required as input for our technique. The angles are calculated for both the objects and compared. A large difference in angles would confirm that the image is manipulated and negligible or relatively very small difference would authenticate the image.

Thus, the original images were selected in different angle combinations, viz., (45°, 75°) or (30°, 60°).

We aim at the detection of the image manipulation. The accuracy is verified using the original images with known and unknown angles. We use standard fake images available over internet for validating our process of the capabilities as a forensic tool. These standard fake images are proved to be manipulated through some different techniques.

Following is the **Pseudo-code** for our proposed process of calculating the angle of incidence at any object:

Ready and open image file

Select the region with the change in shading from bright to dark

Get two copies of the region

If current copy is = Copy 1

Use Decorrelation Stretch

Output Red Band values

End

If current copy is = Copy 2

Acquire Red Band values

Apply Maxfilter to reduce noise

Apply Adaptive Histogram Equalization

Output resultant image

End

Generate n distinct pixel co-ordinate points

If current pixel co-ordinate count is < = n

Record intensity as pixel value from result of Copy1

Calculate surface normal by using three points around the pixel using resultant of copy 2

End

Use least square approximation to calculate best fit model

Find the angle of incidence from the resultant vector

Calculate Error by repeating process

Add the error

Output the final angle

All the images used are in JPEG format and under assumption that the image has objects of interest of size possible to give a low variance block. The block size used is 32×32 and the number of points of interest that is selected for the normal matrix is 400. The 400 coordinate pairs are produced using a random function and avoiding any collision.

Three nonlinear points are used around the points of interest and the normal to that plane was estimated after the adaptive histogram equalization. The average of the pixel value and four neighbours have been used for the intensity value at the point of interest. Least square approximation is carried by finding the quadratic error function given in Ref. 27 to calculate the unknown light direction vector. The angle of incidence is calculated from x and y directions – with 0° lying along the image horizontal.

These steps are repeated several times and then averaged to reduce the errors. The final average matrix gives the direction of light source on the selected object of the image. The process is repeated for multiple objects and the angles of incidence are compared to establish a forgery or to defy it.

5. Experimental results

The following figures [Figs. 4(a)–(d)] represent four images taken in presence of single white light source. The actual angles are the angles calculated geometrically from the figures. Angles calculated are the angles found from the algorithm stated above using the block size of 32×32.

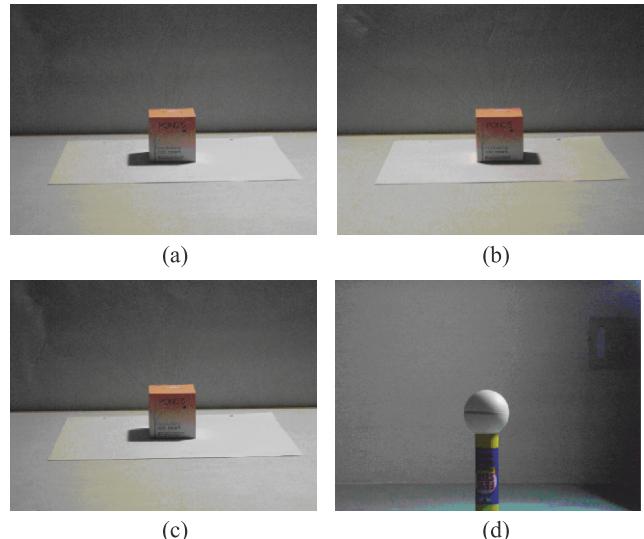


Fig. 4. Four images from the experiment named (a)–(d).

The blocks are selected from a region of uniform texture and intensity gradient. The geometrical verification of the angles is carried out through shadows as explained earlier which are tabulated in Table 1.

Table 1. Light source angle measured for images shown in Fig. 4.

	4(a)	4(b)	4(c)	4(d)
Actual angles	65	-75	69	50
Angles calculated	65.7529	-78.7936	74.419	56.369

Next, we take up the case of simulated forgery in image as shown in Fig. 5 that consists of the ball from Fig. 4(d) placed into Fig. 4(a). On applying our method we again find the angles of these two objects to be 65.7529 and 56.369. The difference is large enough to establish the forgery in the image of Fig. 5.

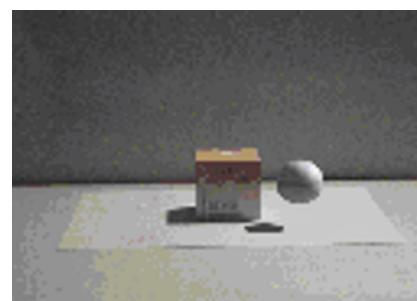


Fig. 5. Simulated image forgery from composite image of Figs. 4(a) and 4(d).

Another example is taken from Flickr.com. Two regions have been selected, one from the lady is black skirt and another from the sari clad lady as shown in Fig. 6. The angles measured by our technique are shown in Table 2.

The insignificant difference between the light source directions of the two women allows us to conclude that image taken has not been modified (both women were actually present there when the image was captured).

Table 2. Angle measured by the proposed technique for the image shown in Fig. 6.

Figure	Angle
6(b)	-76.6677
6(c)	-75.83



Fig. 6. An original image taken from Flickr.com. (above – left) represents an original image and Fig. 6(b) (top) and Fig. 6(c) (down) on right represents 32×32 block selected from shoulders of two women in the photograph.

The next case has been taken from a standard fake image as shown in Fig. 7 [20]. And the measured angles of the three selected regions have been listed in Table 3; they clearly indicate that the image is manipulated.

The angles calculated from our method for the first two patches have low difference, however, the third and the first patch are found with a difference of 10° indicating that the image is manipulated.

Table 3. Angle predicted by the current method for the image shown in Fig. 7.

Figure	Angle
7(B)	-72.9436
7(C)	-75.5802
7(D)	-82.9833

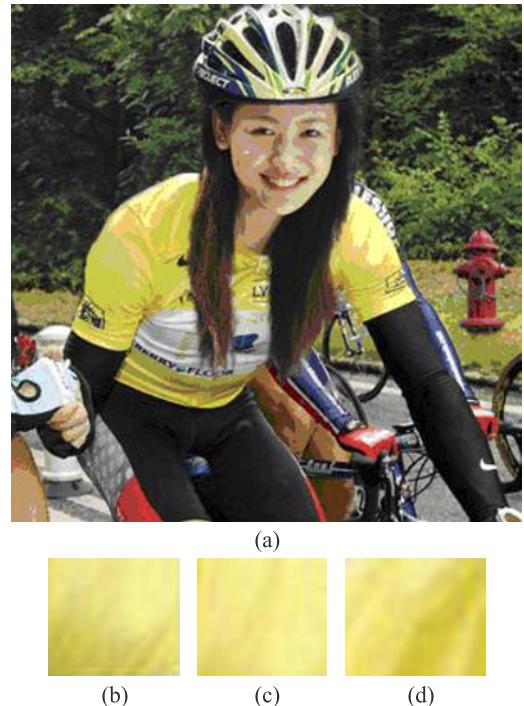


Fig. 7. A set of three regions is extracted from the girl's shoulders to validate if light source directions are consistent.

6. Discussions and conclusions

The shading technique we have used exploits the power of quantity that uses the intensity flow across the object. The technique discussed does not need the image to be converted into grey scale which is realized by weighted average of the RGB values. The grey scale conversion loses the real information while finding weighted average. However, the colours independently are capable of representing information regarding intensity profile and structural profile. The process of digitization introduces some errors in continuous intensity increase or decrease representation on image. The block covering a large number of points lowers the above errors and estimates a better fit model for the angle of incidence of light from the source. The least square approximation provides an easy and efficient best fit model by estimating the unknowns for Eq. (1).

The errors may appear because of the sharp curvatures that occur near the surface boundaries of the object in an image. Thus, the region is selected without any sharp curvatures. The 3D shape of Lambertian surface cannot be uniquely solved with a single viewpoint and an unknown light source, however, using the noise reduction and contrast improving techniques as we have stated, the pixel values can be used to derive the surface structural profile of the object for the localized region which can be used for the calculation of the angle of incidence of the light [24]. We emphasize that this technique is based on the fact that the image forgery is created by inserting, i.e., addition of a foreign object in an image. This does not include deletion of an object or enhancement.

The algorithm in this case could work only on aspect of finding light source direction not as a forensic technique. Thus, if the adversary is extremely careful in selecting images of the similar lighting direction conditions, this light based forensic technique will fail to identify manipulated images. Another constraint is on the relative distances, the angle of incidence would be the same for two objects when the relative distance between objects is much smaller than the relative distance between the objects and the source. Thus, the algorithm works well under certain lighting conditions, *viz.*, an outdoor shoot on a clear sunny day.

The selection of the region for the technique and the number of such regions are based on human judgment. A smooth region is selected without including any sharp curvatures. The number of regions selected for comparing the incidence angles depends on number of objects/part of objects that need the verification of presence at the time when photograph was captured. In case of humans as object, region may be selected from two different people to verify their mutual presence at the time of shoot or regions from face and the rest of the body to verify that the face is not pasted from some other image.

We conclude with the highlights of our proposed solution. This model is applicable only on the daylight outdoor shooting whereby one may consider the sunlight as a single point source. Hence, one may assume that the surface of the image is Lambertian. This also inclusively specifies that noise may not be seen as a major point of concern for such condition of photography. Our method focuses on extraction of how intensity flows on the surface of the image rather than the information of exact surface feature. There lies the novelty in our approach. We needed to separate the intensity profile from the structural profile. We insisted on manual selection of regions of the same texture where one suspects manipulation because we believed manual judgment in catching hold of a forgery was the best so far. Also, we limit our scope to those images only in which manipulation has been done by inserting an alien object in the original image. Our assertion is that the direction of light for that alien object must be different and that can be found using our method. Our method is not recommended to be applied to an image where manipulation is done by deletion or elimination of a part of the image.

References

1. <http://www.sciam.com/slideshow.cfm?id=photo-tampering-throughout-history>.
2. http://www.tothepc.com/pic/photoshop_rally.jpg
3. http://urbanlegends.about.com/library/bl_sarah_palin_bikini_pic.htm.
4. <http://www.expressindia.com/news/fullstory.php?newsid=39673>.
5. H. Pearson, "Forensic software traces tweaks to images", *Nature* **439**, 520–521 (2006).
6. H. Pearson, "CSI: Cell biology", *Nature* **434**, 952–953 (2005).
7. <http://www.voanews.com/tibetan/archive/2008-02/2008-02-19-voa5.cfm?moddate=2008-02-19>.
8. R.C. Gonzalez and R.E. Woods, *Digital Image Processing*, Prentice Hall, New Jersey, 2002.
9. E. Mingolla and J.T. Todd, "Perception of solid shape from shading", *Biol. Cybern.* **53**, 137–152 (1986).
10. M.K. Johnson and H. Farid, "Exposing digital forgeries through specular highlights on the eye", <http://www.cs.dartmouth.edu/farid/publications/ih07.html>.
11. P. Poulin and A. Fournier, "Lights from highlights and shadows", *Proc. Symp. on Interactive 3D, SI3D'92*, 31–38 (1992).
12. <http://www.telegraph.co.uk/news/uknews/1564465/James-Purnell-in-fake-photo-row.html>.
13. Y. Wang and D. Samaras, "Estimation of multiple illuminants from a single image of arbitrary known geometry". *Proc. 7th European Conf. on Computer Vision-Part III, LNCS 2352*, 272–288, Springer-Verlag, London, 2002.
14. B.K.P. Horn, "Height and gradient from shading", <http://people.csail.mit.edu/bkph/AIM/AIM-1105A-TEX.pdf>.
15. P. Nillius and J.O. Eklundh, "Automatic estimation of the projected light source direction", *IEEE Computer Society Conf. on Computer Vision and Pattern Recognition (CVPR'01)*, Vol. 1, 1076 (2001).
16. J. Fridrich, D. Soukal, and J. Lukas, "Detection of copy-move forgery in digital images", *Proc. Digital Forensic Research Workshop*, 90–105 (2003).
17. W. Luo, J. Huang, and G. Qiu, "Robust detection of region-duplication forgery in digital image", *Int. Conf. on Pattern Recognit.* **4**, 746–749 (2006).
18. I. Avcibas, S. Bayram, N. Memon, M. Ramkumar, and B. Sankur, "A classifier design for detecting image manipulations", *IEEE Image Proc.* **4**, 2645–2648 (2004).
19. M.K. Johnson, "Lighting and optical tools for image forensics", *PhD Dissertation*, Dartmouth College, 2007.
20. H. Farid, "Digital image forensics", *Sci. Am.* **6**, 42–47 (2008). <http://www.sciam.com/article.cfm?id=digital-image-forensics>.
21. H. Farid, "Exposing digital forgeries in scientific images", *Proc. 8th Workshop on Multimedia and Security*, 29–36 (2006).
22. <http://grin.hq.nasa.gov/IMAGES/SMALL/GPN-2001-000012.jpg>
23. J.M. Pinel, H. Nicolas, and C.L. Bris, "Estimation of 2D illumination direction and shadow segmentation in natural video sequences", *Proc. Int. Workshop on Very Low Bitrate Video Coding*, 197–202 (2001).
24. J.P. O'Shea, M.S. Banks, and M. Agrawala, "The assumed light direction for perceiving shape from shading", *Proc. 5th Symp. on Applied Perception in Graphics and Visualization*, 2008.
25. T.E. Boult and G. Wolberg, "Correcting chromatic aberrations using image warping", *Proc. IEEE Conf. on Computer Vision and Pattern Recognition*, 684–687 (1992).
26. W. Chojnacki and M.J. Brooks, "Revisiting Pentland's estimator of light source direction", *J. Opt. Soc. Am.* **11**, 118–124 (1994).
27. Y. Wang and D. Samaras, "Estimation of multiple directional light sources for synthesis of augmented reality images", *Graph. Models* **65**, 185–205 (2003).