2020 International Conference on Artificial Intelligence and Signal Processing (AISP)

Traffic Sign Recognition: A Survey

Banhi Sanyal
Dept. of Computer Science
NIT Rourkela, Odisha
Rourkela, India
517CS1009@nitrkl.ac.in

Ramesh Kumar Mohapatra
Dept. of Computer Science
NIT Rourkela, Odisha
Rourkela, India
mohapatrark@nitrkl.ac.in

Ratnakar Dash
Dept. of Computer Science
NIT Rourkela, Odisha
Rourkela, India
ratnakar@nitrkl.ac.in

***Abstract*—In this survey, the need of traffic road safety has been discussed and an overview of traffic sign detection and recognition research works has been provided including novel, breakthrough approaches. Traffic sign databases and its inherent steps: Pre processing, Feature Extraction and Detection, Post processing have been discussed thoroughly. But most importantly an overall comparative study of efficiency over the various machine learning and image processing methods used has been drawn, in spite of the much variety in the used database. The challenges that are faced in spite of the increasing number of researches going on in the field of Traffic Sign Recognition (TSR) are also listed.**

***Index Terms*—Traffic Signs, Machine Learning, Object Detection, Image Processing, Traffic Sign Recognition**

I. Introduction

A report published in 2015 on Global Status Report On Road Safety by World Health Organization (WHO) showed that over 1.2 million people die across the globe annually due to road accidents [1].Thus comes the necessity of advanced driver-assistance systems (ADAS) that reduces human interference in driving and hence providing higher road security. We provide a critical overview of traffic sign detection and also mention the persisting shortcomings in the domain of Traffic Sign Detection and Recognition (TSDR).

The rest of the paper is organized in the following manner. Section II emphasizes on the importance of TSR, discusses about the various databases available and various researches done in the field of TSR. Section III gives analysis. The studied challenges are discussed in Section IV. Section V lists the most commonly faced problems in TSR and algorithms to mitigate them along with future discussions and Section VI gives the concluding remarks.

II. Traffic Sign Recognition (TSR)

Traffic signs are markers present at the side of the road to state restriction, give information or directions. Though most of the signs are colored in bright and distinctive colors than their surroundings, drivers still may miss out these signs due to inexperience or human fault. TSR aims at detecting and recognizing one or multiple signs from a given frame.

A. Database

Database is of huge importance for training detection algorithms. Very few works have been done on languages other than English (Broggi et al. [6] and Gonzalez et al. [9] working on Italian and Spanish characters respectively, Rahman et al. working [18] in Bengali). A few of the most used available databases are mentioned in [22]. The lack of databases leads to some major challenges which will be discussed later.

B. TSR Methodology

The steps of TSR can be broadly divided into the modules of Preprocessing, Feature Extraction and Detection, Postprocessing and is discussed as follows.

1) Preprocessing: The images taken are practically never ideal and hence need corrections before further processing. There are five types of possible corrections.

The first is sensor corrections. Second type of correction is noise removal. Noise can arise due to many reasons and are mainly removed during preprocessing. Multiple processes are available to remove or minimize noise. Geometric corrections can also be necessary. Angle or position of camera and other reasons can introduce geometrical variations in the scene which needs to be removed before further processing. Some features are more robust to geometric variation than others. The last involves color corrections. Colour hues are difficult to work with, and it may not be possible to correct using simple gamma curves and the RGB color space [41].

Binarization is the technique of changing pixel image to binary image. S. Priambada et al. [2] in 2017 used binarization and Tsai et al. [8] in 2017 used binarization on intensity image using Otsu method. Edge dilating is the method of adding pixels to the edges and used in 2017 by S. Priambada et al. [2] for text recognition from image. MSER (Maximally Stable External Regions) identification has been done by Greenhalgh et al. [4] in 2012 through connected components, Greenhalgh et al. [19] used the same technique to offer variations in lighting conditions.

HSV (Hue, saturation and value) model of images has been used by Broggi et al. [6] in 2007 for color segmentation, Gonzalez et al.in 2010 [9] used it with Bag of Visual Words (BOVW) to find out latitude and longitude of panel, Greenhalgh et al. in 2012 used it along with MSER, in 2017 S. Priambada et al [2] used it for colour segmentation whereas Gudigar et al. [11] used it along CLAHE (Contrast Limited Adaptive Histogram Equalization) to enhance image and divide it into inner and outer regions. Tsai et al. [8] RGB to HSV and using Binary Mask find contour of each red regions. In 2003 Benallal et al. [5] used colour segmentation for only

978-1-7281-4458-0/20/$31.00 ©2020 IEEE

segmentation and Zaklouta et al. [14] in 2012 used colour segmentation for red colour enhancement. Novel approaches were also introduced to increase the efficiency in preprocessing for example equiangular polygons [23], proposed system to detect candidate maximally stable external regions (MSERs) which are more robust lighting conditions [4] [19], system to work on spatial distribution of traffic signs [37], a combination of solid image analysis and pattern recognition technique is shown in [15] and can detect traffic signs in mobile mapping data.

2) Feature Extraction and Detection: One very important area of application in image processing is feature extraction and detection, which isolates and detects various local patterns of an image or a frame from a video and is mainly used in optical character recognition.

a) Feature extraction: Feature extraction isolates local patterns and can be done in two levels of techniques i.e. low level techniques and high level techniques.

b) Detection: Region of Interest (ROI) is one of the most studied areas of all time. Support Vector Machine (SVM) has been used in 2017 by Tsai et al. [8] for Speed Limit Sign (SLS) Detection and Lim K et al. [32] used SVM with CNN to verify candidate regions whereas CNN recognizes the traffic sign. Linear Discriminant Analysis (LDA) has been used in 2005 by Stallkamp et al. [10] and Bahlmann et al. [21] in two separate researches for classification using posterior probability for each class. In 2019, Anjan Gudigar et al. [43] extracted GIST features and used LDA as a detector is an effective system in real time due to it low execution time on a PC.

Neural Network is a popular choice in authors for extraction and detection and has been used many researches. A few of noteworthy are Rahman et al. [18] in 2008 used to classify Bengali Text. Romadi et al. [20] in 2014 uses SURF and FLANN. SURF algorithm is used to calculate interest points in two images and FLANN compares between the two. In the same year Zhu et al. [39] used both FCN and CNN as classifers to first predict the coarse regions and then classifies the sign respectively. In 2017 Shustanov et al. [38] used cascaded detectors with HOG features and HAAR features separately to detect candidate positions of traffic sign in an image. R. Prem Kumar et al. [42] in 2019 has used Artificial Neural Network (ANN) for both classification and detection.

3) Post processing: The main objective of this step is to improve the efficiency of detection. Stallkamp et al. [10] in 2012 used post calculating the number of false positives as much as possible. In 2014, Lillo-Castellano et al. [40] used this step to discard non-integral regions, connect fragmented signs, separate signs located at the same traffic post. S. Priambada et al. [2] in 2017 used Lavensthein Distance to improve the performance of OCR in written road signs. Quazi Marufur Rahman et al. [44] in 2019 has used this step to create a False Negative Detector (FND) which is used to calculate the efficiency of a detector based on the number of False Negatives generated.

III. Analysis

We have chosen maximum achieved rate for any system, a number that is commonly supplied by all. The efficiency of a system doesn't only come from its highest achieved efficiency rate but also from the number of false positives rates since it decides how many samples the detection stage analyzes. Hence corresponding false positives are also included wherever possible. The numbers that were not provided in the respective works are not included. Please note that the systems have been tested in different ways and on different inputs. So a direct comparison is not possible.

Table I gives overview of the performance of the different schemes for TSR included in this survey. Table II gives efficiency of some works that recognize only text or text and traffic panel signs. We would here like to emphasize the use of GTSRB as the most commonly used database and English as the prime recognized language. Other languages and database have been used only by a few authors.

Table III shows review of works that use Shape and Color for detection. Here the works of Ruta et al. [23] and Berkaya et al. [13] have introduced new algorithm for finding shapes. The main drawback of these works is that the size of data images as inputs which is as small as three as in the work of Ohara et al. [16], making their efficiency in real life questionable. Table IV gives techniques that have used neural network in at least one of the stage. It is observed that the maximum detection rate gives final rate after detection stage. A few works stick out amongst these. Genetic Based Algorithms(GA and GBA) along with Neural Network is used in [27] [28] which is not yet used in traffic signs recognition algorithms till recent times. It is to be noted that it is not necessary these four tables have no duplicate entries because evidently each work incorporates a number of the techniques to achieve detection and recognition. Hence duplicate entries have been removed wherever felt redundant. Besides, the sequence of the works by no means refer to their relevance in any order. From Table II highest achieved efficiency is of 97.77% in case of text recognition by Ohara et al. in [9] which uses multiple features and Naive Baiyes as classifier. Here it would be apt to comment that the use of multiple and efficient features like SIFT, C-SIFT, Hue-Histogram, Hue-SIFT, RGB-SIFT, TCH increases the efficiency rate. SVM and Naive-Bayes both were used in the experiment and Naive-Bayes gave higher above mentioned efficiency. In Table III 97.04% is attained maximum for Shape for Color Detection which proves that more than often new proposed algorithms work better than standard algorithms. From Table IV, 100% efficiency is attainable under constrained environment.

IV. Discussion

As evident lot of work and research has already been done but there is still enough scope for improvement. There are many challenges in this field. The first being the lack of standard databases. A few standard databases are available but a heavy disparity against non-European database is quite evident. Also annotated video tracks are not available in plenty.

TABLE I
OVERALL COMPARISON OF DIFFERENT SCHEMES INCLUDED IN THIS SURVEY.

Paper	Year	Objectives	Recognition rate (in %)	False Rate (in %)	Database	Remarks
S. Priambada et al. [2]	2017	Char from image	F1: 17 to 60			
Wu et al. [3]	2004	panel/char from video	72			
Gonzalez et al. [9]	2014	Char for i/p image	97.77			
Rahman et al. [18]	2008	Bengali char. from image	91.78	8.22	Bangladeshi	Font affects efficiency
Qian et al. [25]	2015	Digits, English, Chinese characters	93.2	6.5		
Greenhalgh et al. [4]	2012	Video	89			
Romadi et al. [20]	2014	Road sign from video	85			
Broggi et al. [6]	2007	Panels in real time	100		Italian	
Tsai et al. [8]	2017	SLS Recognition Real Time	100		German, Belgium	
Zaklouta et al. [14]	2014	Real time recognition	96.70			SVM worked best
Greenhalgh et al. [19]	2012	Real time traffic road signs	84			
Ruta et al. [23]	2009	Traffic sign real time	85.3			
Gao et al. [12]	2005	Traffic sign recognition	95			
Liu et al. [33]	2014	Recognition by sparse coding	96.95		GTSRB	
Berkaya et al. [13]	2015	Circular traffic sign recognition	97.04		GTSDB	GABOR+LBP+HOG
Nguwi et al. [17]	2006	Road Sign using NN	96			
Ellahyani et al. [29]	2016	Traffic sign recognition using random forest	94.05		GTSDB, STS	
Ellahyani et al. [30]	2016	Traffic sign via cascaded CNN	97.94		GTSRB	
Xie et al. [7]	2016	Multiple object in a framework	98.52		GTSDB, KITTI	
Timofte et al. [31]	2011	Multi view	97.7		Belgium	

TABLE II
COMPARISON PERFORMANCE OF TEXT RECOGNIZING TECHNIQUES.

Paper	Year	Database	Feature Extractor	Remarks	Matcher/ Classifier	Language	Recognition Rate (in %)
S. Priambada et al. [2]	2017		Canny		OCR+Tesseract library	Indonesian	60
Wu et al. [3]	2004		Gaussian Edge detector		Incremental	English	72
Gonzalez et al. [9]	2014		SIFT C-SIFT Hue-Histogram Hue-SIFT RGB-SIFT TCH	NB less computation time	Naive Bayes	English	97.77
Gudigar et al. [11]	2017	BTSC GTSRB	HOS Entropies from bispectrum Texture based[12]	See [12] for details	KNN	English	97.47
Rahman et al. [18]	2008	Bangladeshi	Sobel Convolution		Multi Layer Perceptron	Bengali	91.78

TABLE III
REVIEW OF TECHNIQUES THAT USE SHAPE AND COLOR FOR DETECTION

Paper	Year	Database Size	Feature Extractor	Classifier Used	Recognition Rate (in %)	Remarks
Benallal et al. [5]	2003		RGB colour segmentation			
Berkaya et al. [13]	2015		Proposed algorithm for circular signs	SVM	97.04	Novel idea
Ohara et al. [16]	2002	3 Signs	1NN each for matching shape and colour		>95	No proper database Not applicable in real time
Romadi et al. [20]	2014		Circle by Hough Triangle by Ramer-Douglus-Rucar	SURF & FLAN	85	
Bahlmann et al. [21]	2005		Traffic sign detection	LDA		Also uses motion information.
Ruta et al. [23]	2009	48 signs Polish,Japanese	Equiangular polygons	Gaussian	85.3	Novel idea

Languages other than English, German, Spanish, Indonesian have been deeply neglected or has no database. Authors working on any other language than the above mentioned had to synthesize their own database which affects the size of the

TABLE IV
REVIEW OF TECHNIQUES THAT HAVE USED NEURAL NETWORK IN AT LEAST ONE OF THE STAGES.

Paper	Year	Database	Feature Extractor	Classifier	Recognition Rate (in %)	Remarks
Broggi et al. [6]	2007	Italian	Chromatic Shape	NN for each shape category		
Gao et al. [12]	2005		Color Shape	Nearest Template	95	
Rahman et al. [18]	2008	Bangladeshi	Sobel Edge	Multi layer NN	91.48	
Qian et al. [25]	2015	GTSRB	Viola & Jones	Max pooling CNN		
Bruno et al. [26]	2017	German		CNN	97.25	Multiple Signs
Ellahyani et al. [29]	2016	GTSDB	HOG LBP	SVM NN		
Aghdam et al. [34]	2016	GTSB	HOG	CNN	99.89	Can process 37.72 high resolution img/sec, performance increase y using hard-mining
Aghdam et al. [35]	2016			CNN	99.65	Ensemble
Jin et al. [36]	2014	GTSRB	Local Patterns	CNN	99.65	Hinge loss used
Shustanov et al. [38]	2017	GTSRB GTSDB		CNN	99.94	Android application developed
Zhu et al. [39]	2016	STSD	Coarse sign regions	FCN CNN	100	Object Proposal method Full efficiency on condition
R. Prem Kumar et al. [43]	2019		SIFT DRLBP	ANN		Classifier used for detection as well
Shijin Song et al. [45]	2019	Tshinghua-Tentcent	CNN	CNN	91	CNN compressed to android devices

inputs. As such these methodologies, even if claimed, may not be practical in real life. The lack of database also gives rise to a much bigger issue. Since rarely the authors have used the same inputs to their models, the models are not directly comparable. This has a higher impact on the fact that none of the methods are comparable and hence highest efficiency can not be claimed of any model and hence each work act like standalone models. Another challenge in the field of TSR are the number of works that have reported on actual video tracts to that which have claimed can work on video tracks. TSR is a real time problem and so more and more works should be done on real time videos.

V. Challenges: Issues and Solutions

Listed are some issues and challenges evident from the survey.

The first is illumination perspectives: Illumination changes affects the colour, edges and contrast of the target. Since colour, edge and contrast recognition are some of the main and classic features of the object detection algorithms, therefore, illumination invariant preprocessing algorithms are required. Histogram distribution of luminance channel and statistical properties of order moments can be used to know the illumination condition of an image. Contrast enhancement algorithms and illumination invariant color models like HSV can be used to sharpen the edges and retain color information in poor light conditions etc.

The next is visual perspective. The optical axis of the mounted camera may not be aligned to the target traffic sign and this is highly likely to give arise to deformations of the image. As such circles may appear as ellipse and edge lengths may appear to be different. Generalized Hough Transform handles deformed circles to great extent. Accumulator array creation and further filtering can deal with the problem of deformation and disconnected circles. Scale invariant features like SIFT and SURF can be used in case of size variation. Oriented FAST and Rotated BRIEF (ORB) is a widely used rotation and scale invariant feature. Local Energy based Shape Histogram (LESH) can be used as a scale invariant shape based feature for object detection. These methods along with strong classifiers can solve the problem of perspective deformation.

The next is motion blur. The moving camera poses a natural problem of motion blur which weakens the sharp edges. Hence a restoration process before detection is needed. Various algorithms have been developed to extract stable and sharp edges over frames are optical flow, Point Spread Function modeling. Frequency domain filtering using estimated motion model is also used in motion blur restoration.

The fourth challenge is partial occlusion. Signboards are very easily occluded by other objects like lampposts, hoardings etc. in front of the sign. But the use of regular shape and symmetry keeps them detectable. Part based object detection methods, local binary pattern, histogram of oriented gradient, randomized Hough transform are good classification algorithms for partially occluded signs i.e., handling broken edges. Predictive tracking based algorithms work on edges rather than frames and hence has lower probability. Tracking objects commonly use key points tracking and kernel-based tracking.

The fifth challenge is weather variation. Typical weather conditions like fog, smog, rain droplets lead to problems like totally hiding desired objects from eyes as well as camera or blocking away the edges of the signs partially or totally. Light fog or little rain can be handled by vision based algorithms efficiently. But in case of extreme weather sensors based image techniques like thermal or Light Detection and Ranging (LIDAR) imaging are needed.

The sixth challenge is classifier selection. Any TSR system needs a robust classifier in its geographically used area. This survey shows neural network as one of the classic classifiers used for the traffic sign. Random forest and SVM along with features like HOG or LBP give equally good results.

A perfect blend of a detector and a classifier gives an efficient TSR system.

VI. Conclusion

An attempt has been made to provide a segment wise comparison and analysis of TSR. Also a few other aspects of traffic security has been discussed and cited. While working the prime focus has been to enlist various methodologies possible in the field of traffic security as well as to describe a few of these methodologies with details by analyzing more works at the same time. The model of TSR has been broken into three main modules and each has been discussed and analyzed well. The main challenges have been mentioned and the emerging algorithms to be taken in the field of TSR.

References

[1] Global Status Report On Road Safety 2015 published by World Health Organization(WHO)

[2] S. Priambada and D. H. Widyantoro, "Levensthein distance as a post-process to improve the performance of OCR in written road signs," 2017 Second International Conference on Informatics and Computing (ICIC), Jayapura, pp. 1-6.

[3] Wu, Wen, Xilin Chen, and Jie Yang. "Incremental detection of text on road signs." (2004).

[4] Greenhalgh, Jack, and Majid Mirmehdi. "Real-time detection and recognition of road traffic signs." IEEE Transactions on Intelligent Transportation Systems 13, no. 4 (2012): 1498-1506.

[5] Benallal, Mohamed, and Jean Meunier. "Real-time color segmentation of road signs." Canadian Conference In Electrical and Computer Engineering, 2003. IEEE CCECE . vol. 3, pp. 1823-1826.

[6] Broggi, Alberto, Pietro Cerri, Paolo Medici, Pier Paolo Porta, and Guido Ghisio. "Real time road signs recognition." In Intelligent Vehicles Symposium, 2007 IEEE, pp. 981-986.

[7] Hu, Qichang, Sakrapee Paisitkriangkrai, Chunhua Shen, Anton van den Hengel, and Fatih Porikli. "Fast detection of multiple objects in traffic scenes with a common detection framework." IEEE Transactions on Intelligent Transportation Systems 17, no. 4 (2016): 1002-1014.

[8] Tsai, Chi-Yi, Hsien-Chen Liao, and Kuang-Jui Hsu. "Real-time embedded implementation of robust speed-limit sign recognition using a novel centroid-to-contour description method." IET Computer Vision 11, no. 6 (2017): 407-414.

[9] Gonzalez, Alvaro, Luis M. Bergasa, and J. Javier Yebes. "Text detection and recognition on traffic panels from street-level imagery using visual appearance." IEEE Transactions on Intelligent Transportation Systems 15, no. 1 (2014): 228-238.

[10] Stallkamp, Johannes, Marc Schlipsing, Jan Salmen, and Christian Igel. "Man vs. computer: Benchmarking machine learning algorithms for traffic sign recognition." Neural networks 32 (2012): 323-332.

[11] Gudigar, Anjan, Shreesha Chokkadi, U. Raghavendra, and U. Rajendra Acharya. "Local texture patterns for traffic sign recognition using higher order spectra." Pattern Recognition Letters 94 (2017): 202-210.

[12] Gao, Xiaohong W., Lubov Podladchikova, Dmitry Shaposhnikov, Kunbin Hong, and Natalia Shevtsova. "Recognition of traffic signs based on their colour and shape features extracted using human vision models." Journal of Visual Communication and Image Representation 17, no. 4 (2006): 675-685.

[13] Berkaya, Selcan Kaplan, Huseyin Gunduz, Ozgur Ozsen, Cuneyt Akinlar, and Serkan Gunal. "On circular traffic sign detection and recognition." Expert Systems with Applications 48 (2016): 67-75.

[14] Zaklouta, Fatin, and Bogdan Stanciulescu. "Real-time traffic sign recognition in three stages." Robotics and autonomous systems 62, no. 1 (2014): 16-24.

[15] Salti, Samuele, Alioscia Petrelli, Federico Tombari, Nicola Fioraio, and Luigi Di Stefano. "Traffic sign detection via interest region extraction." Pattern Recognition 48, no. 4 (2015): 1039-1049.

[16] Ohara, Hirofumi, Ikuko Nishikawa, S. Miki, and N. Yabuki. Proceedings of the 9th International Conference on, "Detection and recognition of road signs using simple layered neural networks." in Neural Information Processing, 2002. ICONIP'02. vol. 2, pp. 626-630. IEEE,

[17] Nguwi, Y-Y., and Abbas Z. Kouzani. International Joint Conference on, "Automatic road sign recognition using neural networks." in Neural Networks, 2006. IJCNN'06. pp. 3955-3962.

[18] Rahman, Mohammad Osiur, Fouzia Asharf Mousumi, Edgar Scavino, Aini Hussain, and Hassan Basri. International Symposium on "Real time road sign recognition system using artificial neural networks for bengali textual information box." In Information Technology, 2008. ITSim 2008. , vol. 2, pp. 1-8. IEEE.

[19] Greenhalgh, Jack, and Majid Mirmehdi. "Real-time detection and recognition of road traffic signs." IEEE Transactions on Intelligent Transportation Systems 13, no. 4 (2012): 1498-1506.

[20] Romadi, Mohammed, Rachid Oulah Haj Thami, Rahal Romadi, and Raddouane Chiheb. 9th International Conference on, "Detection and recognition of road signs in a video stream based on the shape of the panels." In Intelligent Systems: Theories and Applications (SITA-14), 2014 pp. 1-5. IEEE.

[21] Claus, Ying Zhu, Visvanathan Ramesh, Martin Pellkofer, and Thorsten Koehler. "A system for traffic sign detection, tracking, and recognition using color, shape, and motion information." in Intelligent Vehicles Symposium, 2005. Proceedings. IEEE, pp. 255-260.

[22] Mogelmose, Andreas, Mohan Manubhai Trivedi, and Thomas B. Moeslund. "Vision-based traffic sign detection and analysis for intelligent driver assistance systems: Perspectives and survey." IEEE Transactions on Intelligent Transportation Systems 13, no. 4 (2012): 1484-1497.

[23] Ruta, Andrzej, Yongmin Li, and Xiaohui Liu. "Real-time traffic sign recognition from video by class-specific discriminative features." Pattern Recognition 43, no. 1 (2010): 416-430.

[24] Welzel, Andre, Pierre Reisdorf, and Gerd Wanielik. "Improving urban vehicle localization with traffic sign recognition." 18th International Conference in Intelligent Transportation Systems (ITSC), 2015 IEEE pp. 2728-2732.

[25] Qian, Rongqiang, Bailing Zhang, Yong Yue, Zhao Wang, and Frans Coenen. 11th International Conference on "Robust chinese traffic sign detection and recognition with deep convolutional neural network." in Natural Computation (ICNC), 2015 , pp. 791-796. IEEE.

[26] Bruno, Diego Renan, and Fernando Santos Osorio. "Image classification system based on deep learning applied to the recognition of traffic signs for intelligent robotic vehicle navigation purposes." in Robotics Symposium (LARS) and 2017 Brazilian Symposium on Robotics (SBR), 2017 Latin American, pp. 1-6. IEEE.

[27] Chen, Zong-Yao, Wei-Chao Lin, Shih-Wen Ke, and Chih-Fong Tsai. "Evolutionary feature and instance selection for traffic sign recognition." Computers in Industry 74 (2015): 201-211.

[28] Wali, Safat B., Mohammad A. Hannan, Aini Hussain, and Salina A. Samad. "Comparative survey on traffic sign detection and recognition: a review." Przeglad Elektrotechniczny, ISSN (2015): 0033-2097.

[29] Ellahyani, Ayoub, Mohamed El Ansari, and Ilyas El Jaafari. "Traffic sign detection and recognition based on random forests." Applied Soft Computing 46 (2016): 805-815.

[30] Xie, Kaixuan, Shiming Ge, Qiting Ye, and Zhao Luo. "Traffic sign recognition based on attribute-refinement cascaded convolutional neural networks." in Pacific Rim Conference on Multimedia, pp. 201-210. Springer, Cham, 2016.

[31] Timofte, Radu, Karel Zimmermann, and Luc Van Gool. "Multi-view traffic sign detection, recognition, and 3d localisation." Machine vision and applications 25, no. 3 (2014): 633-647.

[32] Lim K, Hong Y, Choi Y, Byun H (2017) Real-time traffic sign recognition based on a general purpose GPU and deep-learning. PLoS ONE 12(3): e0173317. doi:10.1371/journal. pone.0173317

[33] Liu, Huaping, Yulong Liu, and Fuchun Sun. "Traffic sign recognition using group sparse coding." Information Sciences 266 (2014): 75-89.

[34] Aghdam, Hamed Habibi, Elnaz Jahani Heravi, and Domenec Puig. "A practical approach for detection and classification of traffic signs using convolutional neural networks." Robotics and autonomous systems 84 (2016): 97-112.

[35] Aghdam, Hamed Habibi, Elnaz Jahani Heravi, and Domenec Puig. "A practical and highly optimized convolutional neural network for classifying traffic signs in real-time." International Journal of Computer Vision 122, no. 2 (2017): 246-269.

[36] Jin, Junqi, Kun Fu, and Changshui Zhang. "Traffic sign recognition with hinge loss trained convolutional neural networks." IEEE Transactions on Intelligent Transportation Systems 15, no. 5 (2014): 1991-2000.

[37] Yuan, Yuan, Zhitong Xiong, and Qi Wang. "An incremental framework for video-based traffic sign detection, tracking, and recognition." IEEE Transactions on Intelligent Transportation Systems 18, no. 7 (2017): 1918-1929.

[38] Shustanov, Alexander, and Pavel Yakimov. "CNN design for real-time traffic sign recognition." Procedia Engineering 201 (2017): 718-725.

[39] Zhu, Yingying, Chengquan Zhang, Duoyou Zhou, Xinggang Wang, Xiang Bai, and Wenyu Liu. "Traffic sign detection and recognition using fully convolutional network guided proposals." Neurocomputing 214 (2016): 758-766.

[40] Lillo-Castellano, J. M., I. Mora-Jiménez, Carlos Figuera-Pozuelo, and José Luis Rojo-Álvarez. "Traffic sign segmentation and classification using statistical learning methods." Neurocomputing 153 (2015): 286-299.

[41] Image Pre-Processing. 2017. semantic scholar. [ONLINE] Available at: https://pdfs.semanticscholar.org/cc43/a71e05cfc49ab0777b82ca94d181f779149f.pdf.

[42] Kumar, R. Prem, M. Sangeeth, K. S. Vaidhyanathan, and Mr A. Pandian. "TRAFFIC SIGN AND DROWSINESS DETECTION USING OPEN-CV." TRAFFIC 6, no. 03 (2019).

[43] Gudigar, Anjan, Shreesha Chokkadi, U. Raghavendra, and U. Rajendra Acharya. "An efficient traffic sign recognition based on graph embedding features." Neural Computing and Applications 31, no. 2 (2019): 395-407.

[44] Rahman, Quazi Marufur, Niko Sünderhauf, and Feras Dayoub. "Did You Miss the Sign? A False Negative Alarm System for Traffic Sign Detectors." arXiv preprint arXiv:1903.06391 (2019).

[45] Song, Shijin, Zhiqiang Que, Junjie Hou, Sen Du, and Yuefeng Song. "An efficient convolutional neural network for small traffic sign detection." Journal of Systems Architecture (2019).