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A Study on the Effect of Radiometric Variations on A Fuzzy Stereo Matching Algorithm: A Statistical Analysis

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Abstract

In recent years, interest towards visually guided autonomous robot has been the research area worldwide due to its outstanding applications in space, mining and under water environment. Despite it has these applications, generation of real time dense depth map for autonomous robots is a research problem that is still being explored. Radiometric variation present in stereo images pairs result in erroneous disparity maps. The proposed algorithm attempts to increase the accuracy of disparity map generated from images with radiometric variations through combining multiple cost functions in a fuzzy inference system. In the present research article, the authors analyzed the results of the mentioned algorithm through a statistical approach. Hence, this paper focuses on development of fuzzy logic model (FLM) based stereo matching algorithm for visually guided autonomous robot under different radiometric variations. This is followed by a statistical analysis on the results obtained from the proposed method. The experiments carried out were designed using Taguchi's design of experiments (TDoE) and desirability function analysis (DFA) was used to identify optimum conditions for minimizing the errors. Finally, a second order model has been generated using response surface methodology (RSM) to correlate the errors obtained by FLM and RSM. From the results obtained through fuzzy stereo matching and response surface methodology, condition 2 (illumination 1 and exposure 1 for both the images) gave the lowest error of (6.7%) (6.8%) for α (0.9) and number of segments (800). Further from desirability function analysis, it is observed that optimal conditions for minimizing the errors (%) under different radiometric conditions is set at alpha (0.68) and number of segments (636). Finally, fuzzy stereo matching results and mathematical model results were fairly close for all tests.

Keywords: Desirability function analysis; Fuzzy logic; Response surface methodology; Stereo matching algorithm; Taguchi's design of experiments.
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1. Introduction

Stereo vision navigation system has been used in wide range of applications such as, robot navigation, augmented reality and automotive applications.[1-7] It is suggested that dense 3D point clouds can be generated by stereo vision using modern techniques. In this work, it is also suggested that local stereo matching methods can estimate the disparity at a point in one image by comparing a small surrounding region with a series of small regions from the other image.[8] The research Ref [9] states that the depth information of the scene, along with the gray value information, which is an important parameter that is used in a wide variety of image processing applications. They also suggested that for accurately analyzing an image, it is essential to acquire depth information. An algorithm that uses fast local AD (absolute differences) on images after checking for left to right consistency, applying a uniqueness constraint and a median filter in.[10] Research work in[11] presented an algorithm that achieves almost real-time performance. The correlation window is chosen adaptively for each region of the picture and it is based on SAD (sum of absolute differences). Apart from that, a left to right consistency check and a median filter are utilized. Several fast and robust techniques for stereo matching are investigated.[12] The authors also proposed that multiple stereo pairs with

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different baselines may be meaningfully combined to improve accuracy of depth estimates.

The research in Ref [13] proposes a new illumination invariant dissimilarity measure that instead of red green blue (RGB), utilizes the hue saturation intensity (HIS) colour space. The correct significance weights are assigned through the incorporation of gestalt theory on the pixels while cost aggregation. The only negative aspect stated by the authors is that under ideal lighting conditions, the performance of their proposed algorithm might be slightly lower than the intensity based ones. The authors claim that the proposed method preserves the details of the image is able to overcome non-uniformities in luminosity. A methodology that utilizes a triangular window, as compared to the conventional square or rectangle shaped windows, wherein the vertices are defined through a corner detection algorithm is presented in Ref [14]. The matching of the generated triangles is performed with respect to length and area length of corresponding sides.

The organization of this article is as follows, Section 2 discusses the recent literature in this area, research method employed for this research article is mentioned in Section 3, followed by the results and discussions in Section 4 and the conclusion in Section 5.

2. Related work

The authors in Ref [15] worked on images with radiometric differences. The proposed method initially computes the disparity using a modified census transform, which uses mean intensity of the pixels within the comparison window. Correspondence matching was carried out through normalized cross correlation (NCC) on the modified image. The evaluation proves that the proposed method is robust in a variety of illumination and exposure conditions. A method for stereo matching based on comparing features obtained from SIFT algorithm is proposed in Ref [16]. Initially the fundamental matrix if found from which the epipolar geometry between the given stereo pair can be obtained. The probability of the valid match is improved by considering relative positions of the neighbours using the Euclidian distance between neighbours. The proposed algorithm was used to derive the disparity map for satellite images. A diagonal anchor based adaptive shape support region generation based on diagonal arm length and the confidence level which controls gray value similarity in the support region is proposed in Ref [17].

Middlebury data sets are used to test the performance of the algorithm. It was compared with tradition common methods of stereo matching like sum of absolute differences (SAD), sum of squared differences (SSD) and NCC algorithms and was claimed to demonstrate much better behavior in the preservation of image details and the generated disparity map is observed to have better quality among the mentioned methodologies. An area based stereo matching algorithm which uses edge distances as a similarity measure is presented in Ref.[18] For computation of disparities, these similarity measures were presented to a fuzzy inference system and the whole architecture was implemented on a field programmable gate array (FPGA). A feature based stereo matching method was proposed by the authors in Ref [19]. The features detected were edges in the images through fuzzy edge detectors. The similarity measure used in the research work was determined through correlation of fuzzy sets. Instead of finding the disparity of every pixel in the image, the authors were able to be generated sparse disparity maps due to the fact that they used only certain points in the images as features for similarity measure. The research work presented in Ref [20] uses multi resolution images for the purpose of generating dense disparity maps. Fuzzy logic was used to determine the resolution level with which the matching needs to begin for each image region.

A genetic fuzzy algorithm was proposed in Ref [21] for stereo matching. To determine the matching possibility metric, a fuzzy formulation of the similarity assumption is used. A fuzzy fitness function using matching possibilities and disparity smoothness is defined to evaluate individuals. The authors claimed that the results show improved accuracy and computational time. A statistical analysis of a stereo matching algorithm was presented in Ref [22]. The authors used a corner matching algorithm and were able to generate an analytical model of the matching process with which the effects of varying the parameters in the matching algorithm can be computed directly. The authors state that the methodology presented here can be used as a general model for feature matching and can be used for determining any future modifications to corner detection and matching processes.

A methodology where multiple data costs were combined through a fuzzy approach is presented in Ref [23]. The appropriate number of fuzzy rules were selected through experimentation by varying the parameters of the membership functions of the inputs and the outputs. From the literature it was observed that there has been hardly any evidence related to application of TDoE, DFA and RSM on stereo matching algorithm for visually guided autonomous robot under different radiometric variations but these approaches have been effectively used in analyzing the effects of process parameters selected in mechanical and medical applications.

Hence this paper discusses on development of fuzzy logic model (FLM) based stereo matching algorithm followed by statistical approach such as TDoE, DFA and RSM.

3. Stereo matching algorithm under radiometric conditions

In fuzzy stereo matching used in this research both the left and right images are initially segmented such that each segment contains pixels of similar intensities. Following which, these segmented images are subjected to similarity matching through ‘Data cost 1’ and ‘Data cost 2’. The results generated through these similarity matching metrics are presented to the fuzzy disparity generator which provides the appropriate disparity values based on the results of the similarity metrics

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(results of 'Data cost 1' and 'Data cost 2').

Inspired from Ref [23] this research work utilizes NCC along with normalized mutual information (NMI) and gradient of SAD as shown in Eq. 1 and Eq. 2,

$$Data\ cost\ 1 = NCC \quad (1)$$

$$Data\ cost\ 2 = \alpha * NMI + (1-\alpha) * Grad\ of\ SAD \quad (2)$$

The proposed methodology was tested against datasets with varying radiometric conditions. The exposure and illumination conditions vary as condition 0, condition 1 and condition 2. Every image pair is represented as ($L_E L_I\_R_E R_I$), where L_E, R_E represent the exposure conditions of the left and right image, while L_I, R_I represent the illumination conditions of the left and right image respectively. The effect of different number of segments and the weight 'α' (alpha), which decides the level of importance given to a certain similarity measure in a linear combination of two similarity metrics, was observed and found that the initial assumption of increasing the number of patches for images with more variation in intensities, to

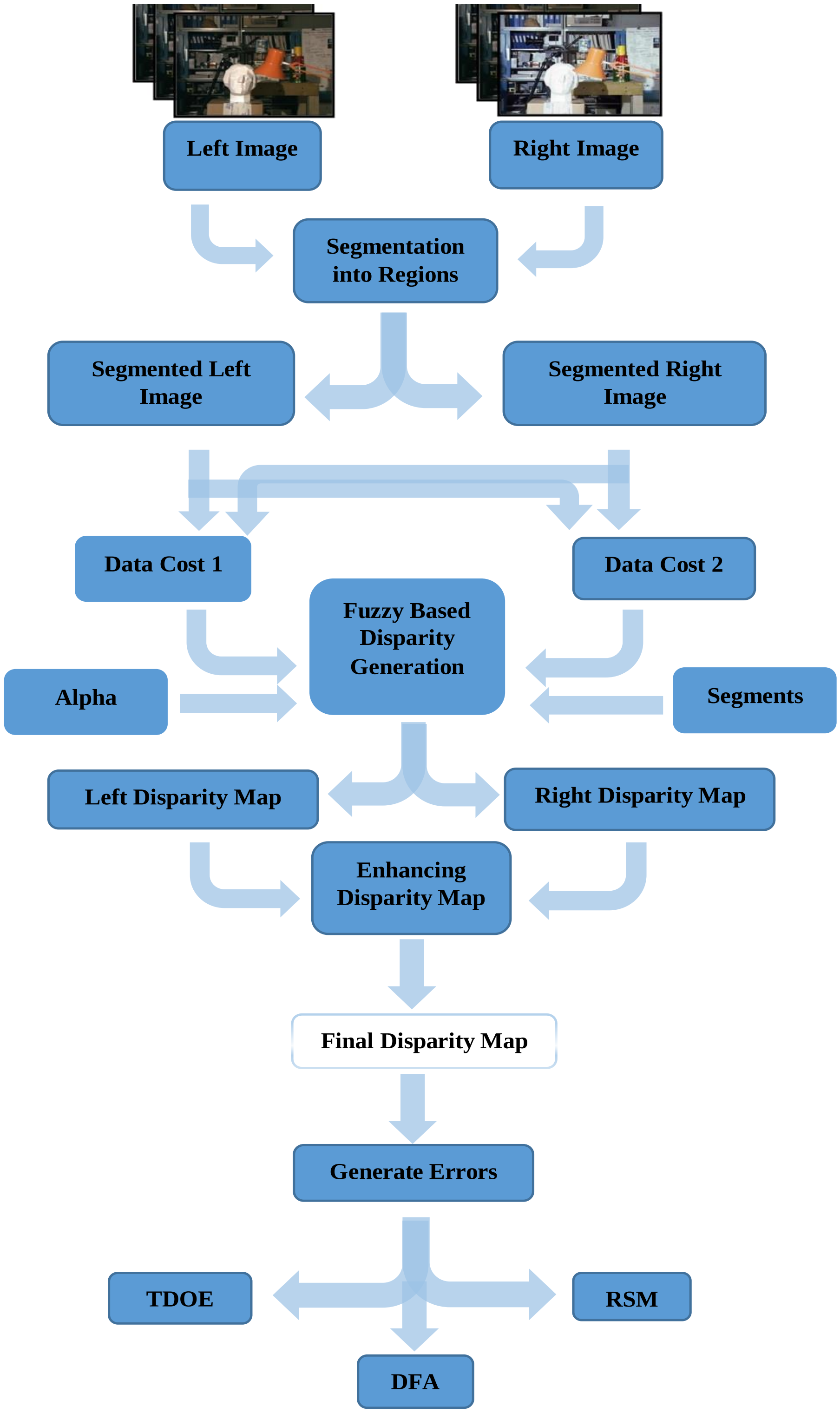

Fig. 1 Schematic representation of the proposed methodology.

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provide a better result, was found to hold true. The schematic representation of the proposed methodology is presented in Fig. 1.

TDoE helps in formulating experimental layout and obtaining optimum conditions using Signal-to-Noise (S/N) ratio characteristic (smaller the better) by Eq. 3[24] to generate valid and objective conclusions and is being widely followed in various manufacturing and engineering applications.[25-31] The Taguchi technique helps us understand the best levels of a quality characteristic with a minimum variation. Due to this reason, it has played a major role for researchers in various applications. It has also proved to operate consistently and optimally for a variety of conditions. In the present research, we attempt to utilize this methodology in the field of image processing and observe the effects of various combinations of inputs and lighting conditions in the images in terms of errors obtained from Taguchi L9 orthogonal array (Eq. 3).

$$\frac{S}{N} = -10\log\frac{1}{x}\left(\sum q^2\right) \tag{3}$$

where, x is the number of observations and q is the observed data.

RSM is a widely used technique for identification of optimum process output variables with minimum number of experimental runs.[32,33] In this research a second order mathematical model based stereo matching algorithm under different radiometric variations in terms of errors has been generated.

The relationship between the segments and alpha can be expressed as follows (Eq. 4):

$$Error\ (\%) = \beta_0 + \beta_1 * alpha + \beta_2 * segments + \beta_3 * alpha^2 + \beta_4 * segments^2 + \beta_5 * alpha * segments \tag{4}$$

DFA[34,35] is the prediction tool which is used for optimizing multi process output variables. According to this approach, quality characteristics and desirable output variables can be identified with less number of experimental trails. Mathematical expressions related to DFA is reflected in the Eqs. S1-S3 of the Supplementary Materials. In this study, the desirability function approach is used for optimizing the output variable using response surface methodology.

The mathematical representation of Mamdani fuzzy inference system, NMI, NCC, and Gradient of SAD were adopted from Ref[36,37]. The equations that define DFA, RSM and TDoE are appended in the supplementary section. The dataset used for this experiment were obtained from the Middlebury Stereo vision benchmark which is a standard platform for researchers working in this area.[38] For stereo matching algorithms a more conclusive performance measure is the percentage of the bad pixels in the disparity map generated by the stereo matching algorithm. Hence that is the measure we have considered for our experiments.[39,40]

4. Results and discussion

4.1 Fuzzy stereo matching

Stereo matching was performed with the left image (reference image) having a fixed radiometric condition (exposure 1 and illumination 1) while the radiometric conditions of the right image (target image) were varied from 0 to 2, thus resulting in six different conditions ((1) to (6)).

The present work was conducted using a Mamdani fuzzy inference system. The rules for the fuzzy system are presented in Table 1.

Table 1. Fuzzy system rules.

Rule number	Data cost 1	Data cost 2	Output
1	Poor	Poor	Poor
2	Poor	Very bad	Poor
3	Poor	Bad	Very bad
4	Poor	Average	Bad
5	Poor	Good	Average
6	Poor	Very good	Average
7	Very bad	Poor	Poor
8	Very bad	Very bad	Very bad
9	Very bad	Bad	Very bad
10	Very bad	Average	Bad
11	Very bad	Good	Below average
12	Very bad	Very good	Below average
13	Bad	Poor	Very bad
14	Bad	Very bad	Very bad
15	Bad	Bad	Bad
16	Bad	Average	Below average
17	Bad	Good	Average
18	Bad	Very good	Average
19	Average	Poor	Bad
20	Average	Very bad	Bad
21	Average	Bad	Below average
22	Average	Average	Average
23	Average	Good	Above average
24	Average	Very good	Good
25	Good	Poor	Below average
26	Good	Very bad	Below average
27	Good	Bad	Average
28	Good	Average	Above average
29	Good	Good	Good
30	Good	Very good	Very good
31	Very good	Poor	Average
32	Very good	Very bad	Average
33	Very good	Bad	Above average
34	Very good	Average	Good
35	Very good	Good	Very good
36	Very good	Very good	Best

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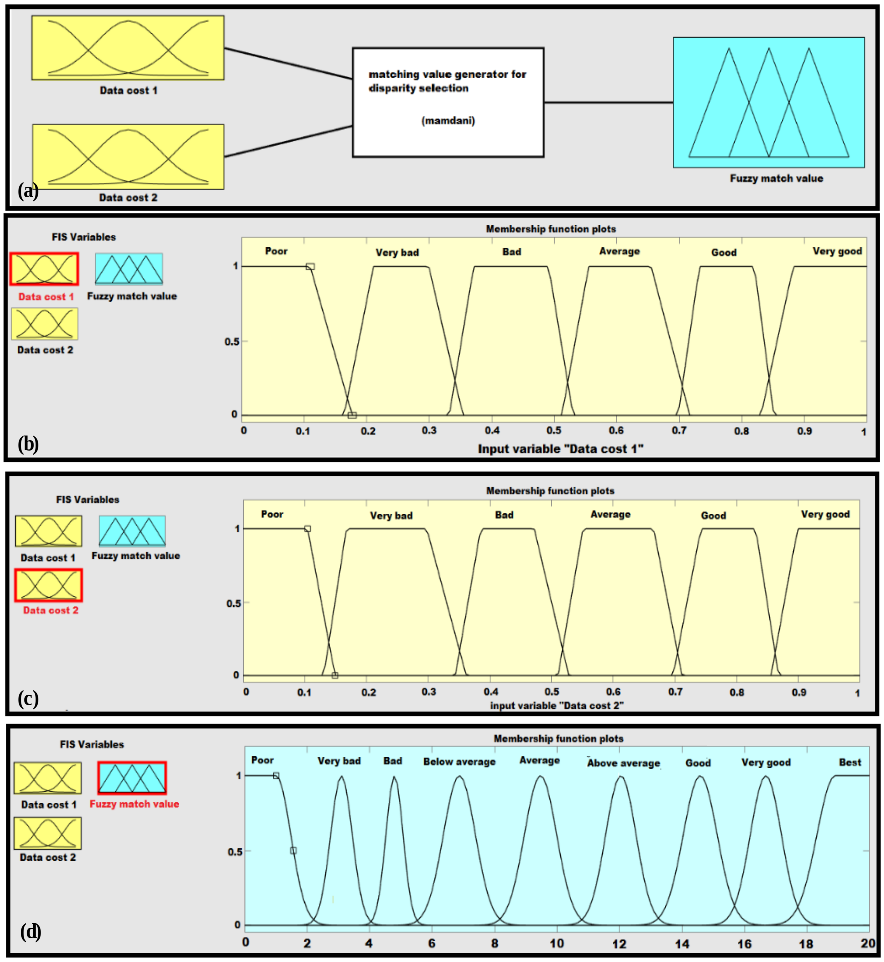

Fig. 2 (a) Overview of fuzzy inference system; (b) membership function of input 1; (c) membership function of input 2; (d) membership function of output.

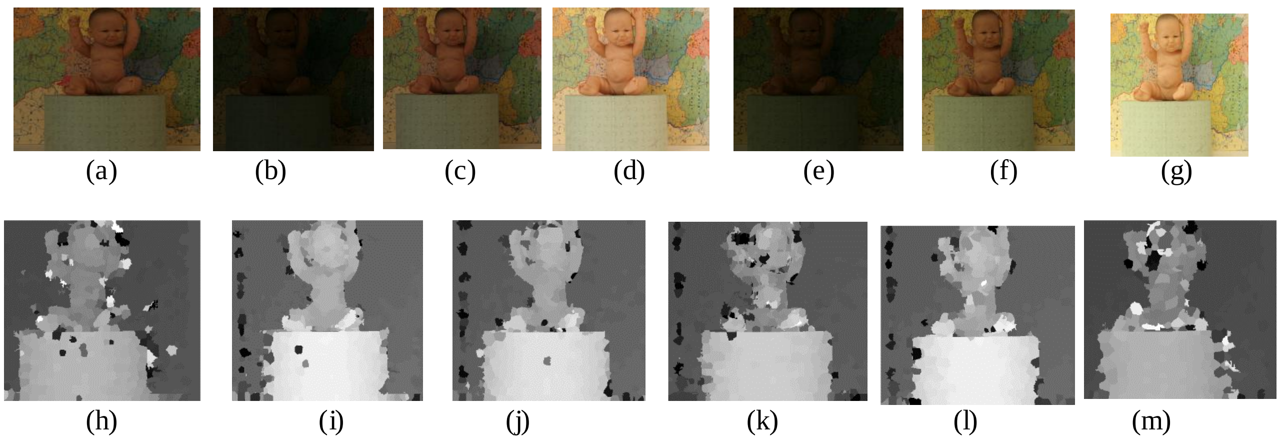

Fig. 3 (a) Left reference image, (b) to (g) corresponding right images with radiometric conditions, (h) to (m) respective disparity maps obtained through the proposed methodology.[36,37]

We have implemented the FIS through the matrix laboratory (MATLAB) 2018 graphical user interface (GUI). As mentioned previously, two inputs were fed into the FIS. Fig. 2 presents a bird's eye view of the two-input fuzzy inference system that we have used. A set of sample images with various radiometric variations and the effect of these variations on the generated disparity map is shown in Fig. 3.

In condition 1, it was found that when the lighting condition of the right image was set to 10 (exposure (1), illumination (0)), the lowest error was obtained for alpha (0.7) and number of segments (700), while the highest error was obtained for alpha (0.1) and number of segments (500). When the lighting condition was varied to condition 2, the lowest error was obtained for alpha (0.9) and number of segments

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(800), while the highest error was obtained for alpha (0.1) and number of segments (600). For lighting condition 3, exposure and illumination is set to 1 and 2 in the right image respectively. The lowest error was obtained for alpha (0.6) and number of segments (700), while the highest error was obtained for alpha (0.1) and number of segments (700). Condition 4 indicates exposure condition 2 and illumination condition 0. The lowest error was obtained for alpha (0.8) and number of segments (600), while the highest error was obtained for alpha (0.1) and number of segments (800). With exposure condition 2 and illumination condition 1, the lowest error was obtained for alpha (0.5) and number of segments (600), while the highest error was obtained for alpha (0.1) and number of segments (800). The sixth condition indicates both the exposure and illumination condition being set to 2. The lowest error was obtained for alpha (0.8) and number of segments (600), while the highest error was obtained for alpha (0.1) and number of segments (800).

4.2 Taguchi's design of experiment

The data means of main effects plot obtained from TDoE was to examine the effects of selected set of process input parameters significantly influencing the process output parameter *i.e.* error (%) during different radiometric conditions. From main effects plot for means and S/N ratios for error (%) (Figs. 4 and 5) the optimum conditions for minimum error (%) can be established at, alpha (0.9), segments (800) for radiometric condition 1, alpha (0.9), segments (700) for radiometric condition 2, alpha (0.5), segments (700) for radiometric condition 3, alpha (0.9), segments (700) for radiometric condition 4, alpha (0.5), segments (700) for radiometric condition 5 and alpha (0.9), segments (800) for radiometric conditions 6.

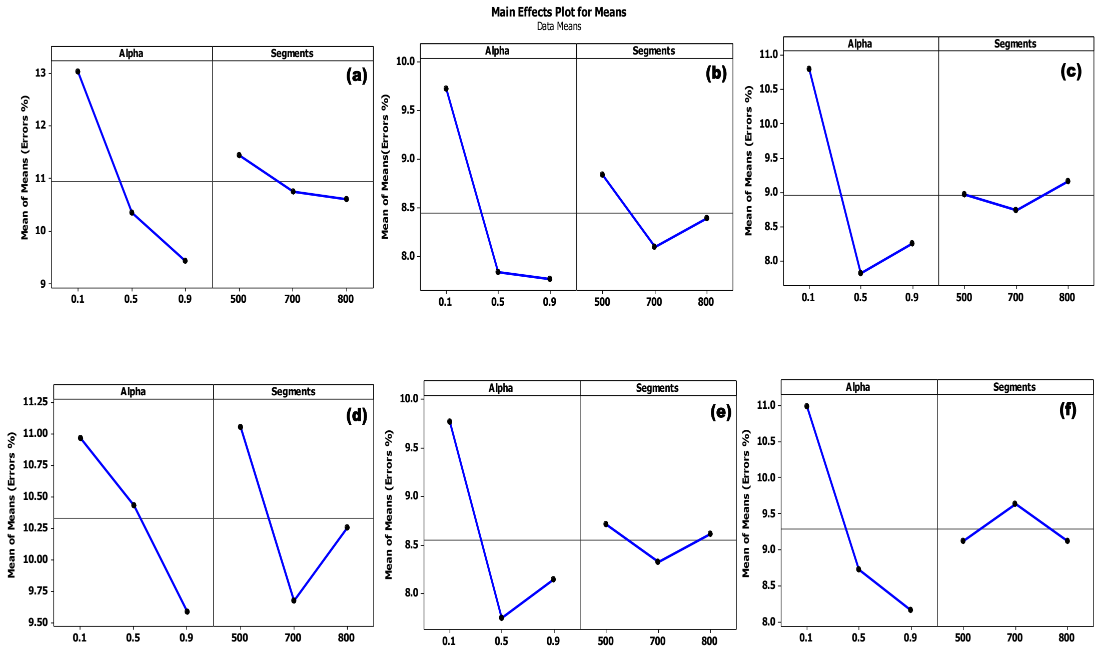

Fig. 4 (a) to (f) depicts the mean of means for errors (%) under different radiometric conditions (1) to (6).

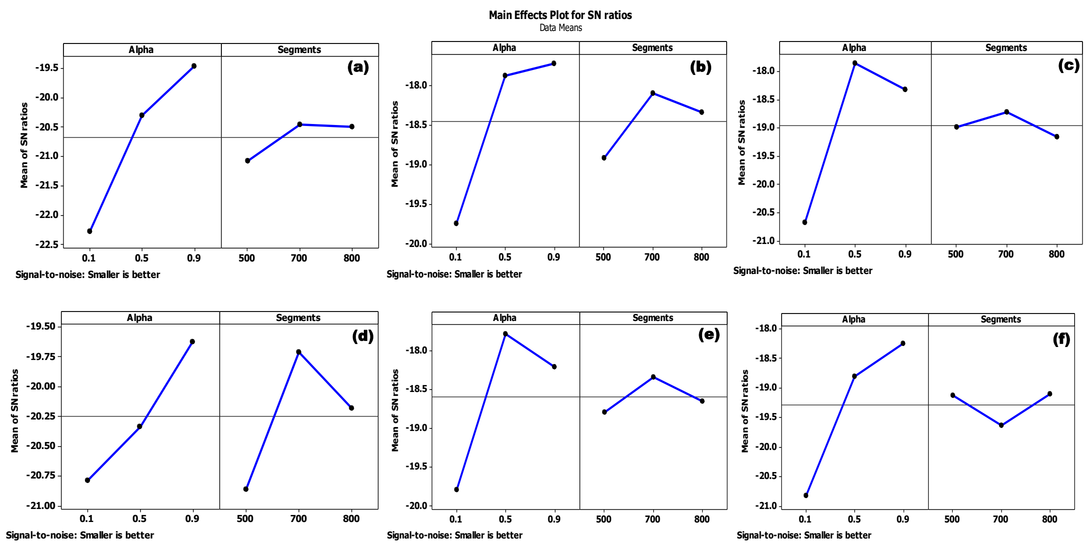

Fig. 5 (a) to (f) depicts the mean S/N graph for errors (%) under different radiometric conditions (1) to (6).

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Table 2. (a) to (f) ANOVA table for response function of the errors under different radiometric conditions (1) to (6).

Source	DF	Seq SS	Adj SS	Adj. MS	F	P
Regression	5	22.3575	22.3575	4.4715	8.31	0.007
Residual Error	7	3.7672	3.7672	0.5382		
Total	12	26.1347				

(a)

Source	DF	Seq SS	Adj SS	Adj. MS	F	P
Regression	5	15.0497	15.04973	3.00995	77.88	0.000
Residual Error	7	0.2706	0.27056	0.03865		
Total	12	15.3203				

(b)

Source	DF	Seq SS	Adj SS	Adj. MS	F	P
Regression	5	21.5214	21.5214	4.30429	67.65	0.000
Residual Error	7	0.4454	0.4454	0.14846		
Total	12	21.9668				

(c)

Source	DF	Seq SS	Adj SS	Adj. MS	F	P
Regression	5	7.72547	7.72547	1.54509	9.12	0.006
Residual Error	7	1.18603	1.18603	0.16943		
Total	12	8.91150				

(d)

Source	DF	Seq SS	Adj SS	Adj. MS	F	P
Regression	5	10.2529	12.25292	2.05058	14.10	0.000
Residual Error	7	0.3492	0.34921	0.04989		
Total	12	10.6021				

(e)

Source	DF	Seq SS	Adj SS	Adj. MS	F	P
Regression	5	13.7943	13.7943	2.75885	32.62	0.000
Residual Error	7	0.5921	0.5921	0.08459		
Total	12	14.3864				

(f)

Table 3. RSM model results for errors (%) under different radiometric conditions.

Conditions	Parameters		Error (%)
	Alpha	Segments	Model value
1	0.7	700	9.151
2	0.9	800	6.8042
3	0.6	700	7.3887
4	0.8	600	9.0248
5	0.2	700	8.067
6	0.8	600	7.9525

4.3 Response surface methodology

The second order response surface representing the errors (%) can be expressed as a function of input parameters such as alpha and number of segments. The relationship between the errors (%) and input parameters has been expressed as follows (Eq. 5):

$$Error\ (\%) = \beta_0 + \beta_1 * alpha + \beta_2 * segments + \beta_3 * alpha^2 + \beta_4 * segments^2 + \beta_5 * alpha * segments \quad (5)$$

From the observed data for errors (%), the response function for all radiometric conditions has been determined in uncoded units as mentioned in supplementary section.

Table 2 presents the result of ANOVA for the response function. This analysis is carried out for a 5% level of significance, *i.e.* for at 95% level of confidence. Observing the values of Table 2, it is evident that, the calculated F value is larger than the value of the F-table for the mentioned degrees of freedom and hence we can conclude that the generated second order response function is quiet adequate.

From Eqs. S4-S9 contour and surface plot for every response surface at various radiometric conditions are plotted (Fig. 6). These contours and surface plot can aid in the estimation of the errors (%) at any zone of the selected region. It is evident from the Table 3, that the errors (%) was minimum of 6.8% under the radiometric condition 2 which falls when alpha (0.9) and segments (800) compared to other radiometric conditions.

A similar methodology was followed for the remaining datasets and a comparison of the parameter values which

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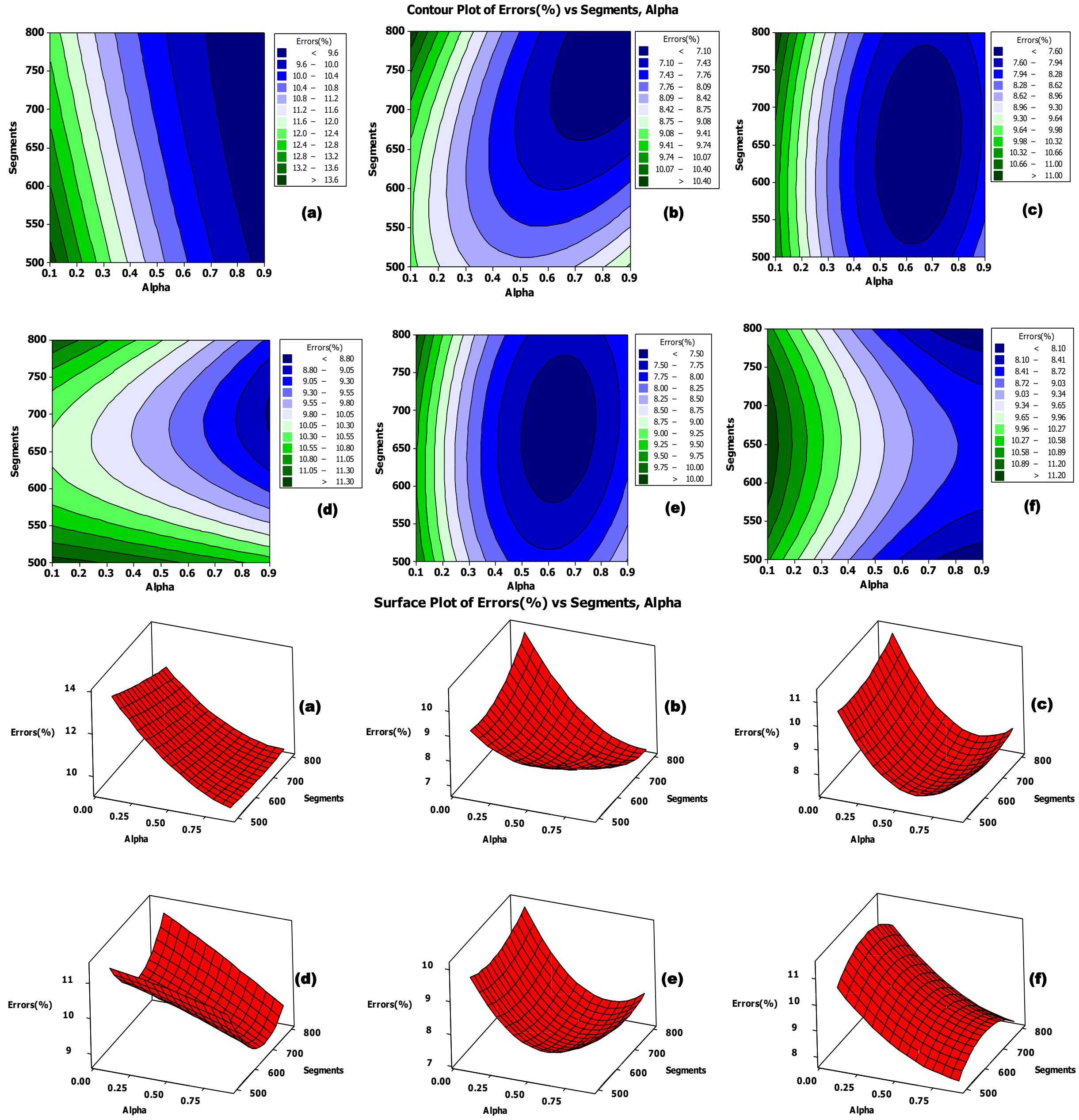

Fig. 6 (a) to (f) depicts errors (%) contour plot and surface plot in alpha - segment planes under different radiometric conditions (1) to (6).

generate the least error is mentioned in Table S1.

4.4 Desirability function analysis

According to this approach, quality characteristics and desirable output variables can be identified with less number of trails. In this study, the desirability function approach is used for optimizing the errors (%) for different radiometric conditions using response surface methodology. The desirability function achieves this task by transforming the output variables into dimensionless variables called desirability index di. The range of a desirability index falls in the closed interval [0, 1].

In this paper, a second order response surface model is fit to the data selected, to model the correlation between the output variables and the input variables under different radiometric conditions. Then, the individual desirability of these output variables are calculated for estimating the overall desirability.

From the results obtained for errors (%) (Fig. 7) for the quality characteristics smaller is the better values are considered for optimizing the multi-response parameter design problem it is observed that optimal conditions for minimizing the errors (%) under different radiometric conditions is set as alpha (0.68) and number of segments (636). Further from Fig. 7 it is evident that minimum error (%) generated using desirability function approach was 7.21% for second radiometric condition.

5. Validation test

To predict and verify the errors (%) in the proposed stereo

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matching algorithm for different radiometric conditions with respect to the chosen initial parameter setting, verification tests are utilized. (Fig. 8) displays the validation of FSM results with RSM model results for the errors (%). Test numbers 1 to 9 shows the comparison of FSM results with mathematical model results obtained from Eqs. S4-S9. It can be concluded from the results that the predicted value is the fairly close to the experimental values for all tests. The comparison of the proposed algorithm with similar methods has been carried out.[37]

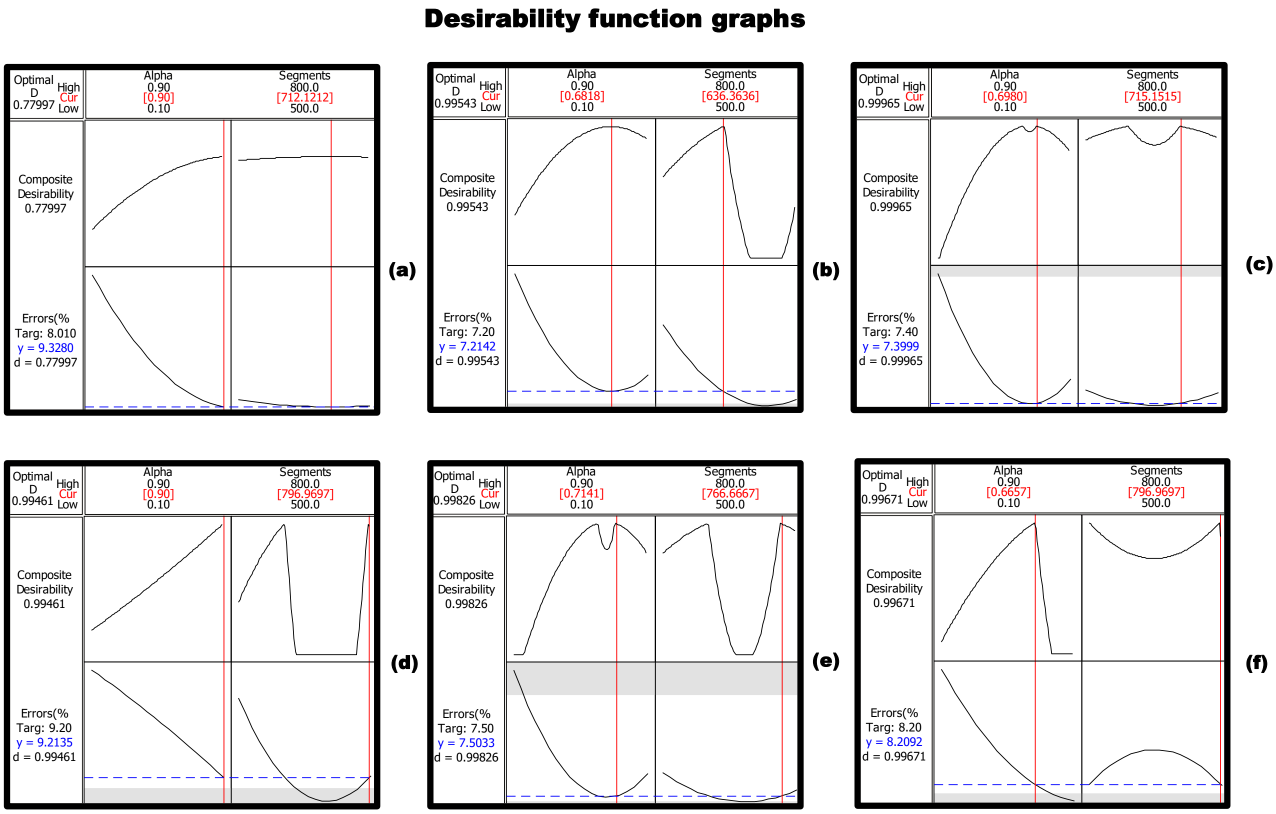

Fig. 7 (a) to (f) plots the composite desirability factor for (1) to (6) conditions.

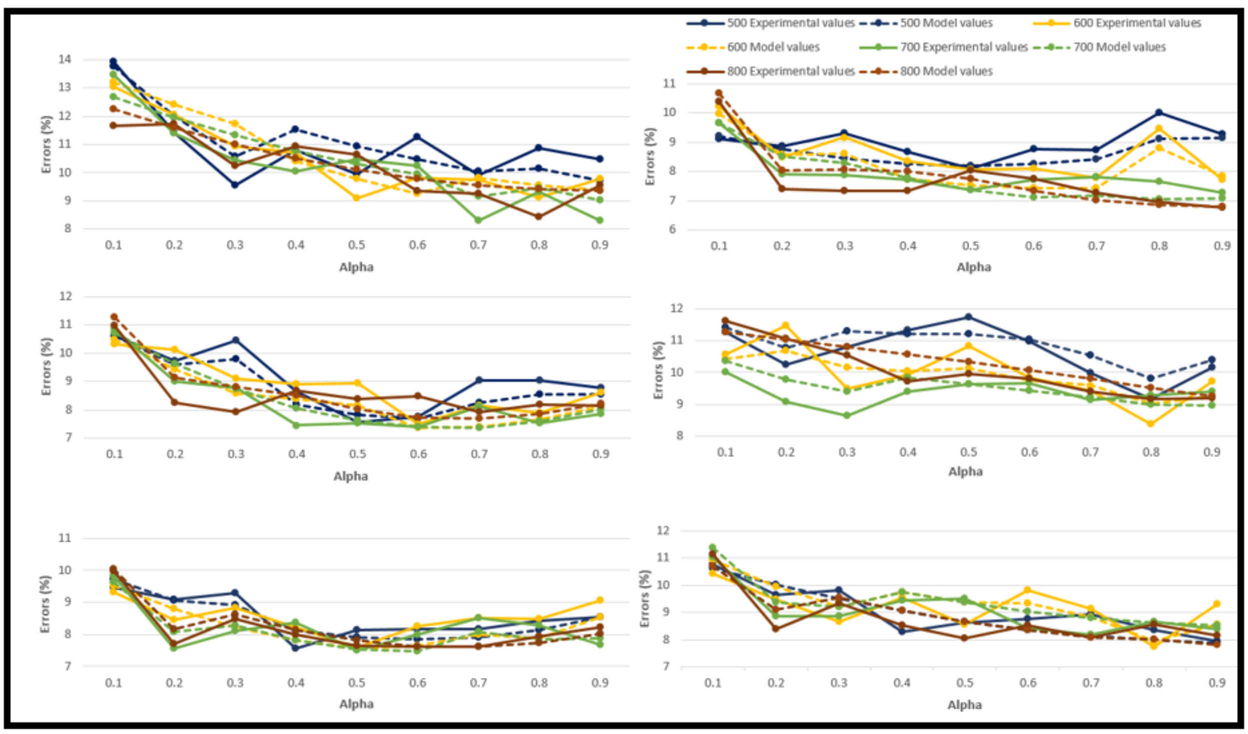

Fig. 8 Comparison between the errors generated by the models and the actual through experiments for (1) to (6) radiometric conditions.

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6. Conclusions

An application of fuzzy stereo matching, TDoE, Response surface methodology and Desirability function analysis on errors (%) under different radiometric conditions has been studied. The reasonable agreement obtained between the FSM, TDoE, Response surface methodology and Desirability function analysis results indicate that the proposed method appears to be suitable for selecting the parameter values for minimizing the errors (%) under different radiometric conditions.

The critical observations derived from the above research work are as follows:

1. From fuzzy stereo matching for condition 2, it was observed that lowest error of (6.7 %) for α (0.9) and number of segments (800) and highest error (10.6%) was obtained for α (0.1) and number of segments (600).
2. From response surface methodology, it is clear that the errors (%) was minimum of 6.8% under the radiometric condition 2 which falls when alpha (0.9) and segments (800) compared to other radiometric conditions.
3. From response surface methodology, it was observed from response contours and surface plot can help in the prediction of the errors (%) at any zone of the selected domain. Further it is clear, that the errors (%)was minimum of 6.8% under the radiometric condition 2 which falls when alpha (0.9) and segments (800) compared to other radiometric conditions.
4. Result of ANOVA for the response function for a level of significance of 5%, i.e., for a level of confidence of 95%, it is apparent that, the F calculated value is greater than the F-table value and hence the second order response function developed is quiet adequate.
5. From desirability function analysis, it is observed that optimal conditions for minimizing the errors (%) under different radiometric conditions is set at alpha (0.68) and number of segments (636).
6. Fuzzy stereo matching results and mathematical model results were fairly close for all tests and can be effectively used under different radiometric conditions.

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Conflict of interest

There are no conflicts to declare.

Supporting information

Applicable.

Abbreviations

FLM	Fuzzy Logic Model
TDOE	Taguchi's Design of Experiments
DFA	Desirability Function Analysis
RSM	Response Surface Methodology
ANOVA	Analysis of Variance
RGB	Red Green Blue
SAD	Sum of Absolute Differences
NCC	Normalized Cross Correlation
NMI	Normalized Mutual Information
SIFT	Scale Invariant Feature Transform
FPGA	Field Programmable Gate Array
Adj MS	Adjusted Mean of Squares
Adj SS	Adjusted Sum of Squares
F	Fishers Test
P	Probability Statistic
α	Tuning Factor
m	Number of output variables
y	Output variable
y min	Minimum output variable
y max	Maximum output variable
y target	Target output variable
DF	Degrees of Freedom
x	Number of observations
q	Observed data

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