

Light Field Based Depth Estimation

Conventional and Deep Learning Solutions

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This work delves into the field of light field depth estimation, reviewing both conventional and cutting-edge algorithms for predicting disparity information from a light field image. Two of these methods are experimentally validated, and deep learning-based approaches are also discussed, with several potential improvements explored through experimentation. Traditional methods for depth estimation from light field images suffer from the challenge of high computational costs and the difficulty of handling occlusion, making the use of learning-based algorithms highly attractive. The aim of this study is to explore the potential to utilize learning-based algorithm to balance computational cost and depth estimation accuracy, providing accurate and detailed disparity information from a light field image. Although the numerical improvements observed in this study were not significant, the results contribute to a better understanding of light field depth estimation and stimulate further research in this field. The findings of this study may also have practical implications in the development of more efficient and accurate algorithms for estimating depth information from light field images.

CCS CONCEPTS • Machine learning • Computer graphics • Artificial intelligence

Additional Keywords and Phrases: Light Field, Depth Estimation, Deep Learning, Multi-view Stereo

1 INTRODUCTION

LF depth estimation is an essential aspect of computer vision research, as it provides critical geometric information about a scene. This information is fundamental to various research applications, such as view synthesis and image segmentation. Moreover, LF technology has the potential to offer superior performance compared to traditional methods that rely on single images or video sequences. With the increasing prevalence of plenoptic cameras and simplified LF acquisition methods, LF depth estimation could become a promising breakthrough in computer vision.

The research topic of light field (LF) depth estimation poses a significant challenge due to the need to extract depth information from an LF image that contains dense and regularly sampled views. Conventional approaches to this problem that rely on geometric matching, light field structure, or refocusing techniques are not very suitable for real-world applications. These optimization-based methods are often computationally complex and lack flexibility. Furthermore, obstacles such as occlusion and texture-less regions can adversely impact the LF structure.

With the rise of deep learning, an increasing number of researchers are applying it to depth estimation. In comparison to optimization-based methods, deep learning only requires pre-training and can quickly predict scene depth, while also being more robust to noise and occlusion. Additionally, deep learning is not significantly impacted by algorithm complexity or computation time. However, the application of deep learning to light field algorithms is still limited, and the training phase is constrained by training data and network structure.

To gain a better understanding and explore this issue further, this article discusses a series of classical algorithms and prominent deep learning-based methods from recent years. The focus is on experimentally validating two of these methods. In section 4, the article discusses possible changes to LFattNet and provides partial experimental results. Due to the large number of training parameters and the complexity of the model, some ideas have not been experimentally validated. However, reference ideas and code for further exploration are provided.

2 RELATED WORK

Light field images contain multiple viewpoints of a scene, making depth estimation possible with light field cameras. However, the short baselines between the multiple viewpoints can lead to matching errors. Currently, methods for depth estimation in light fields can be broadly categorized into conventional (optimization-based) methods and learning-based methods. Some learning-based methods are developed based on the theoretical foundation of optimization methods. In this section, I selected one classic algorithm from each category to explain in detail.

2.1 Optimization-based Methods

2.1.1 Multi-views matching.

Depth estimation based on multi-view matching is evolved from traditional stereo matching methods for 2D images. Traditional stereo matching methods require two or more cameras to capture a scene, which requires overcoming camera shake and human operation. In contrast, a light field camera captures a scene as if from multiple cameras at once and is almost unaffected by camera shake, making it very promising for depth estimation. Taking the Lytro Illum as an example, each microlens captures 225 light rays from the main lens in a 15x15 pixel array behind it. Selecting the same position behind each microlens can generate an image from a specific viewpoint. Traversing the 15x15 pixels behind each microlens can generate 225 different perspective images. These images have different viewing angles or disparities, which can be used to calculate depth using a matching method.

However, due to the short baseline of light field cameras, matching errors are common. Accurate matching pairs are critical for multi-view matching-based depth estimation. Jeon et al. proposed a subpixel multi-view stereo matching algorithm to achieve sub-pixel accuracy matching, which solves the problem of a short baseline to some extent. The core of this algorithm is the use of phase-shifting theory, in which a small spatial displacement in the time domain is a product of the exponentiation of the displacement in the frequency domain of the original signal. To enable matching between sub-view images, the authors designed two different cost functions: Sum of Absolute Differences (SAD) and Sum of Gradient Differences (GRAD). The final matching cost C is a function of pixel position x and disparity layer l , as shown in the following formula:

$$C(x, l) = \alpha C_A(x, l) + (1 - \alpha) C_G(x, l)$$

where C_A is defined as:

$$C_A(x, l) = \sum \sum \min (|I(uc, x) - I(u, x + \Delta x(u, l))|, \tau)$$

It is constructed by comparing the differences between the central view image $I(uc, x)$ and the other views $I(u, x)$, repeatedly moving a small distance around the pixel x in a specific sub-view and subtract it from the central view until all sub-views ($i=1 \dots N$) have been compared. By using aforementioned phase-shifting theory, the pixel intensity after displacement can be obtained, and Δx increases linearly with the distance between the viewpoints and the central viewpoint. Furthermore, SGD loss is calculated in both x and y directions, and the weighting of the cost function in both directions is determined by the relative distance between any viewpoint and the central viewpoint. Lastly, the authors established a multi-label optimization model and an iterative optimization model to optimize the depth map.

2.1.2 EPI based method

Unlike the multi-view stereo matching method, the EPI method estimates depth by analyzing the structure of the light field data. The slope of the diagonal line in the EPI image can reflect the depth of the scene. The larger the horizontal displacement in the EPI image, the larger the disparity corresponding to the diagonal line, indicating a smaller depth.

The earliest work of EPI for depth estimation was proposed in 1987 by Bolles et al. for structural depth estimation under a moving background, based on the color consistency principle assumption[1]. However, this approach lacked robustness against occlusion and noise. Subsequent work by Zhang et al.[2] sought to enhance the robustness of EPI-based methods to strong occlusion and noise by measuring the slope of the EPI using a rotating parallelogram operator. The operator was integrated into the two-dimensional EPI, measuring the partial distance between two parts of the window. Wanner et al. [3] estimated the local direction of lines using the structure tensor in EPI's spatial domain, and then introduced a smooth optimization to construct global depth.

One representative algorithm is the large scene reconstruction method proposed by Kim et al in 2013[4]. The slope m of a line segment associated with a scene point at distance z can be expressed as:

$$m = 1/d = z/fb,$$

where d is the image space disparity between a pair of images captured at adjacent positions or the displacement between two adjacent horizontal lines in an EPI. f is the camera focal length in pixels, and b is the metric distance between each adjacent pair of imaging positions.

The authors used a fine-to-coarse approach to estimate depth in the EPI by starting at the highest resolution edges, propagating the information, and gradually reducing the EPI resolution. The first step is to calculate edge confidence to determine which pixels in the EPI image may have potential for depth estimation. If there is a large color difference between two pixels, they may correspond to different depths in the light field. Then, the algorithm computes depth estimates for

confident EPI-pixels in the light field image E . It performs the computation per scanline in the EPI, assigning a depth estimate to each EPI-pixel using a modified Parzen window estimation. The algorithm also computes the refined confidence as a measure for the reliability of a depth estimate. To eliminate the influence of outliers, a bilateral median filter is applied to preserve the localization of depth discontinuities.

EPI-based methods exhibit excellent performance when the depth undergoes continuous changes along a straight line in space. However, when the line is interrupted by occlusion or noise, these methods may produce erroneous predictions. Although some algorithms as Kim's are efficient and robust to noisy measurements and occlusions, the introduced constraints such as piecewise processing can increase the algorithm's complexity.

2.1.3 Defocus-based method

An important feature of a light field camera is that it allows post-capture refocusing, which is based on the light field shear principle. By measuring the "blur" of each pixel at different focal planes, its corresponding depth can be estimated. One representative algorithm is proposed by Tao et al. Tao's algorithm utilizes the entire light field image captured by the sensor for computation. During the refocusing process, it obtains the sensor image at different focal planes and calculates the correspondences between different images, i.e., the matching relationships of images captured from different viewpoints.

Specifically, for different depth stacks, Tao's algorithm extracts defocus cues and correspondence cues separately. Defocus is defined as

$$D_\alpha(x) = \frac{1}{|W|} \sum |\Delta x L_\alpha(x')|$$

where W represents the window size of the current pixel neighborhood, Δx represents the horizontal Laplacian operator, and $L_\alpha(x')$ is the refocused light field image after averaging.

Furthermore, correspondence cue is defined as

$$C_\alpha(x) = \frac{1}{|W|} \sum |\sigma_\alpha(x')|$$

where $\sigma_\alpha(x')$ represents the standard deviation of the intensity of each macro-pixel.

Based on these two cues, maximizing spatial contrast can obtain the depth corresponding to defocus clues, while minimizing angular variance can obtain the depth of correspondence. Finally, global optimization was performed on these two depth maps using Markov Random Field (MRF).

2.2 Learning-based Methods

Deep learning has been widely applied in the field of computer vision. In the problem of light field depth estimation, learning-based methods are mainly based on two approaches. The first approach involves fusing different features using models in order to achieve more accurate optimization. The second approach involves optimizing the computation cost. These two mainstream approaches are respectively referred to as EPI-based and cost volume-based methods, as described in paper [5].

2.2.1 EPI-based:

The most representative EPI-based model is EPINet[6], which is often used as a benchmark for comparison when developing new algorithms. The characteristic of this network architecture is that it stacks the light field data from four different angles and then performs the stacked convolution operation on features from each angle, aiming to capture the

relationships between the features from different angles. Each direction of the sub-aperture image corresponds to a network branch that is responsible for encoding and extracting features from images in the corresponding direction. Each branch of the network consists of three fully convolutional modules, where each module includes a $Conv \rightarrow Relu \rightarrow Conv \rightarrow BN \rightarrow Relu$ block. To address the problem of short baseline, a 2×2 convolution kernel is used with a stride of 1. The results obtained from the four directions are concatenated and input into the subsequent convolutional blocks. Finally, it uses the $Conv \rightarrow Relu \rightarrow Conv$ structure to obtain sub-pixel-level estimation precision.

On the basis of EPINet, some researchers have made effective improvements. Leistner et al. [13] introduced EPI-shift, which enables virtual shifting of LF stacks, allowing for the retention of a small receptive field to be effective in the case of wide-baseline. Li et al. [15] constructed an oriented relation module to extract oriented relation features between the center pixel and its neighborhood from EPI patches. Li et al. [16] incorporated the transformer into LF depth estimation and combined EPI feature extraction with transformer to establish global features.

2.2.2 Cost Volume-based:

Some algorithms have optimized the computational consumption of depth estimation while obtaining more accurate results by constructing cost volumes and designing elaborate loss functions. In 2020, Tsai et al. proposed LFattNet [7], which utilizes a view selection module to prioritize important views and reduce redundancy in order to effectively utilize all views for more accurate depth estimation. The proposed architecture is shown in figure 1. Specifically, to extract unary features from each sub-aperture view of the light field image, four basic residual blocks are used, followed by a spatial pyramid pooling (SPP) module to extract context information and generate effective feature maps. These feature maps are concatenated into a 5D cost volume across all sub-aperture views. Before sending the cost volume for disparity regression, an attention-based view selection module is applied to obtain an attention map that specifies the importance of each view. The cost volume is combined with the attention map and sent to the disparity regression module, which produces the disparity map for the center view in the light field image.

Another

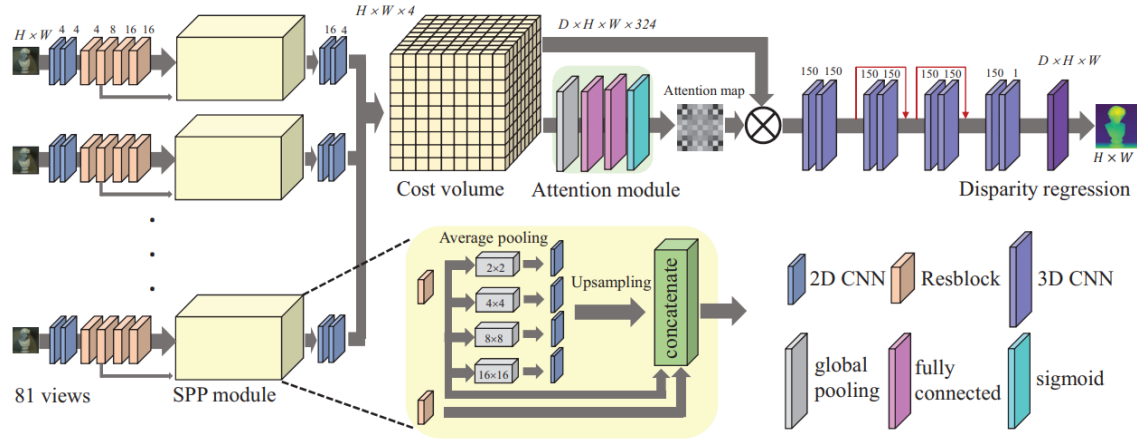


Figure 1: The architecture of LFattNet[7]

Table 1: Styles available in the Word template

Style Tag	Definition	Style Tag	Definition
Title_document	main title of article	ListParagraph	list items
Subtitle	subtitle of article	Statements	math statements
Authors	author name	Extract	block quotations
Affiliation	author affiliation information	Algorithm	caption for algorithm
		Caption	
AuthNotes	footnote to author(s)	AckHead	heading for acknowledgements
Abstract	abstract text	AckPara	acknowledgements text
CCSHead	heading for CSS Concepts	GrantSponsor	sponsor of grant
CCSDescription	CSS terms	GrantNumber	number for the grant
KeyWordHead	heading for keywords	ReferenceHead	heading for references
Keywords	keywords text	Bib_entry	references
ORCID	author's ORCID #	AppendixH1	appendix heading level 1
Head1	heading level 1	AppendixH2	appendix heading level 2
Head2	heading level 2	AppendixH3	appendix heading level 3
Head3	heading level 3	TableCaption	title of table
PostHeadPara	first paragraph after a heading	TableHead	column head of table
		TableFootnote	footnote to table
Para	Subsequent paragraphs of general text	Image	figures
ParaContinue	flush left text after display items like math equations, lists etc.	DOI	Digital object identifier
DisplayFormula	numbered math equation		
DisplayFormulaUnnum	unnumbered equations	Label	label ^a
ComputerCode	Display Computer codes	In-text code	intext computer code
Short Title	Short title of article	History	Dates of article

^a This is example of table footnote.

Tables can be very difficult for people using screen reader technology to understand unless they include markup that explicitly defines the relationships between all the parts (i.e.: headers and data cells). *A key to making data tables accessible to screen reader users is to clearly identify column and row headers.* In Word, authors should identify which row or rows contain column headers. Below are the steps to do this:

1. Select that table's row, then right-click the row and select "Table Properties";
2. In the *Table Properties* window, click the *Row* tab and select the box that says "Repeat as header row at the top of each page."

Or

Apply the "table head" style by highlighting the respective row and applying the "**TableHead**" style found in the "Body Element" section of the ACM Master Article Template.

2.3 Figures

Figures are "float elements" which should be inserted after their first text reference, and have specific styles for identification. Insert a figure and apply the "**Image**" paragraph style to it. For the figure caption, apply the style "**FigureCaption**."

To accommodate readers with color vision differences, figures should still be usable when printed in grayscale. Refer to elements of the figure with non-color terms, for example "indicated as squares" instead of "indicated in blue". Use different patterns in bar charts, different line patterns in graphs, and different shapes in plots to distinguish groups of elements and reinforce color differences.

2.3.1 Half Width Figures.

Figure 1 is an example of a figure and caption spanning the half-page width (one column in a two column format) with the styles applied. If your figure contains third-party material, you must clearly identify it as such, as shown in the example below.



Figure 1: 1907 Franklin Model D roadster. Photograph by Harris & Ewing, Inc. [Public domain], via Wikimedia Commons.
(<https://goo.gl/VLCRBB>)

2.3.2 Full Width Figures.

Figure 2 is an example of a figure and caption spanning the full-page width with the styles applied. If your figure contains third-party material, you must clearly identify it as such, as shown in the examples.

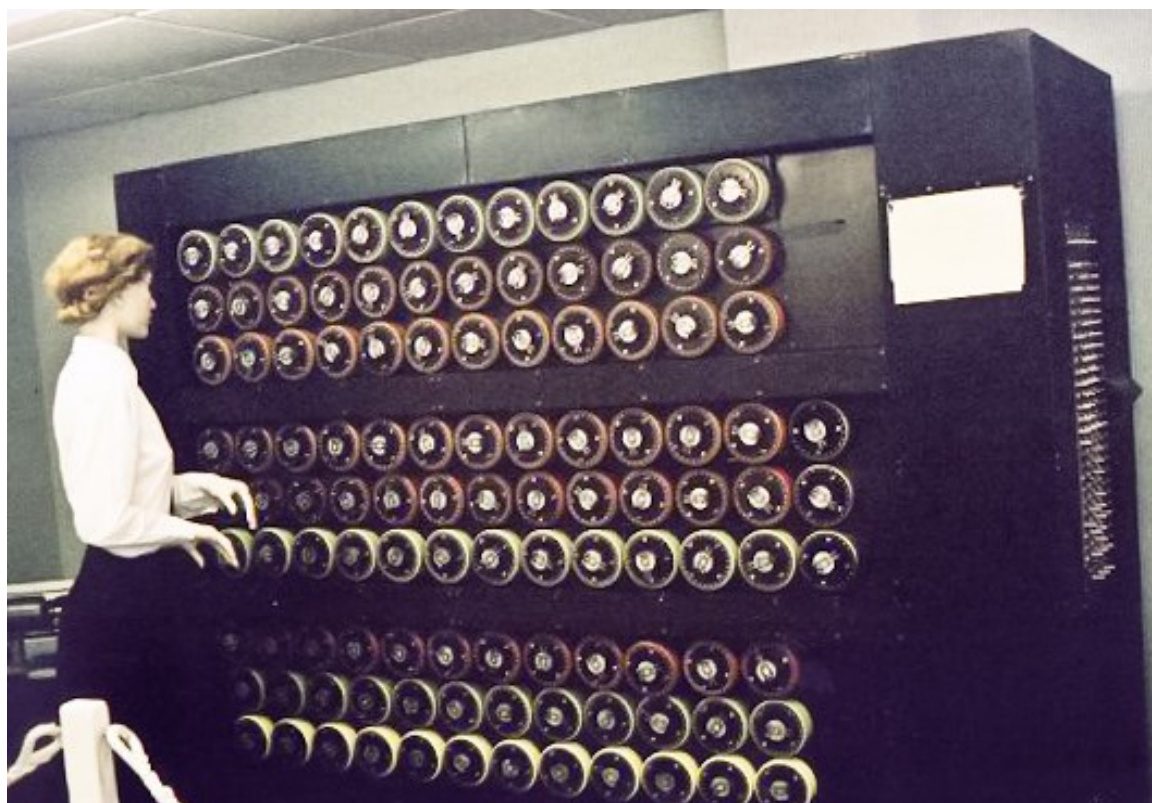


Figure 2: Mockup of a bombe machine at Bletchley Park. Photograph by Sarah Hartwell. [Public domain], via Wikimedia Commons. (<https://commons.wikimedia.org/wiki/File:TuringBombeBletchleyPark.jpg>)

2.3.3 Multi-part figure.

Authors can also insert a multi-part figure above a single caption. Every inserted figure must have the “Image” style applied. Below are instructions regarding how to insert a multi-part figure in your paper.

- If the author wants to insert two multi-part images, they must draw a one row and one column table and insert the images one-by-one in the cells.
- If the author wants to insert three multi-part images, they must draw a one-row and three-column table and insert the images one by one in all three cells.
- If the author wants to insert four multi-part images, they must draw a two-row and two-column table and insert the images one-by-one in all four cells. (see the following example):

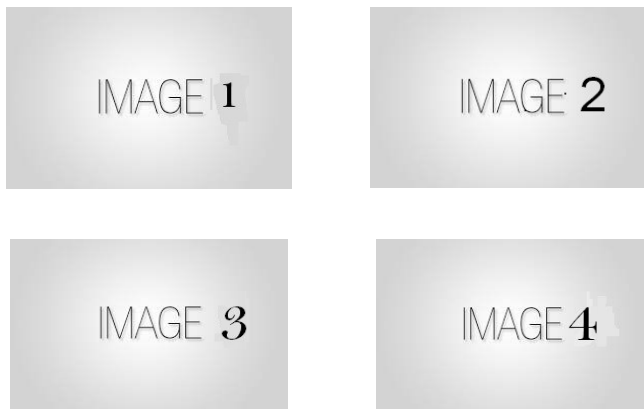


Figure 3: The layout of multipart images should be as per the above example within the table. All images must have the “Image” style applied.

2.3.4 Figure Descriptions.

Every figure should have a figure description unless it is purely decorative. These descriptions convey what’s in the image to someone who cannot see it. They are also used by search engine crawlers for indexing images, and when images cannot be loaded.

A figure description must be unformatted plain text less than xxx characters long. Figure descriptions should not repeat the figure caption – their purpose is to capture important information that is not already provided in the caption or the main text of the paper. For figures that convey important and complex new information, a short plain text description may not be adequate. More complex alternative descriptions can be placed in an appendix and referenced in a short figure description. For example, provide a data table capturing the information in a bar chart, or a structured list representing a graph. For additional information regarding how best to write figure descriptions and why doing this is so important, please see <https://www.acm.org/accessibility>.

The instructions below describe the required steps authors need to follow in order to insert descriptive text for figures (alt-txt value) in **MS Word 2019 on Windows or Word 2016 and later on Mac**:

1. Insert a picture in the document.
2. Right-click the image and select “Edit Alt Text”.
3. In the “alt text” section, provide your text description of the image.

Below are the steps to insert figure descriptions in **MS Word 2013 and 2016**:

1. Insert a picture in the document.
2. Right click on the inserted picture and select the **Format Picture** option.
3. In the settings at the right side of the window, click on the “Layout & Properties” icon (3rd option).
4. Expand **Alt Txt** option.
5. In the “Title” and “Description” text boxes, type the text you want to represent the figure, and then click “Close.”

Below are steps to insert the alt-txt value in **MS Word 2010/2011 for Windows***:

1. Insert a picture in the document.

2. Right click on the inserted picture and select the **Format Picture** option.
3. Select the **Alt Text** option from the left-side panel options.
4. In the “Title” and “Description” text boxes, type the text you want to represent the picture, and then click “Close.”
 - * The Mac 2011 version 14.0.0 and later allows the option for inserting “alt-text.” In the MAC version of Word 2016, right-click on the image and select “Edit Alt Text” from the pop-up menu and then enter the description for the alt text.

2.4 Quotations and Extracts

There are styles for block quotations, which should be used for quotes that are separated from in-line text. Below is an example.

“Microsoft tried to revive the idea of an assistant with Clippy, who began popping up in Microsoft Office in 1997. Its creator, Kevan Atteberry, was actually contracted by Microsoft to design Clippy, which, funnily enough, he did on a Mac ... Sure, people could disable Clippy, but the fact he was on by default angered people.”
[10]

2.5 Equations

There are two types of math equations: the *numbered display math equation* and the *un-numbered display math equation*. Below are examples of both.

2.5.1 DisplayFormula.

The **DisplayFormula** style is applied in the numbered math equation. A numbered display equation always has an equation number (label) on the right.

$$\frac{x = -b \pm \sqrt{b^2 - 4ac}}{2a} \quad (1)$$

2.5.2 DisplayFormula.Unnum.

The **DisplayFormulaUnnum** style is applied only in unnumbered equations. An unnumbered display equation never contains an equation number Bertot and Grimes (2012) on the right—this element distinguishes it from the numbered equation.

$$\frac{x = -b \pm \sqrt{b^2 - 4ac}}{2a}$$

Please note: the subsequent text after the **DisplayFormula** (numbered equation) or **DisplayFormulaUnnum** (unnumbered equation) must have the paragraph style **ParaContinue** applied.

2.6 Math statements

Math statements should have the “Statement” style applied.

Theorem/Proof/Lemma. Math statements should have the “**Statement**” style applied. This paragraph is an example of the “**Statement**” style.

2.7 Algorithms

Algorithms use the styles “AlgorithmCaption” and “Algorithm”.

ALGORITHM 1: Iterative Algorithm

```
current_position  center
current_direction up
current_position is inside circle
while current_position is inside circle, do
    neighborhood all grid hexes within two hexes from current_position
    for each hex in neighborhood, do
        for each neuron in hex do
            convert neuron_orientation to vector
            scale vector by neuron_excitation
            vector_sum vector_sum + vector
        end
    end
    normalize vector_sum
end
```

3 COMPUTER CODE

Display Computer codes can be inserted using “ComputerCode” style.

```
CHAT Start
SAY Welcome to my world
WAIT 1.2
SAY Thanks for Visiting
ASK Do you want to play a game?
OPT Sure
OPT No Thanks
```

Similary, this is an example of intext code text.

Similary, this is an example of intext code text.

4 CITING RELATED WORK

This section cites a variety of journal [5, 15], conference [1, 6, 8, 12, 13], and magazine [3] articles to illustrate how they appear in the references section. It also cites books [9, 10], a technical report [7], a PhD dissertation [4], an online reference [14], a software artifact [11], and a dataset [2].

As you build your article, you should note where you will be placing citations. If you are using numbered citations and references, the reference number - "...as shown in [5]..." is sufficient. If you are using the "author year" style, a reasonable

placeholder is the primary author's last name and the year of publication - "...as shown in [Harel 1978]..." - we will be updating this placeholder later in the process with the citation label as generated by the Word macros in the "master template.

ACKNOWLEDGMENTS

Acknowledgments are placed before the references. Add information about grants, awards, or other types of funding that you have received to support your research. Author can capture the **grant sponsor information**, by selecting the grant sponsor text and apply style 'GrantSponsor'. After this, select grant no and apply 'GrantNumber' from style panel. Example of Grant sponsor: [Competitive Research Programme](#) and example of Grant no: [CRP 10-2012-03](#).

5 HISTORY DATES

In case of submissions being prepared for Journals or PACMs, please add history dates after References as (*please note revised date is optional*):

Received November 2019; revised August 2020; accepted December 2020

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A APPENDICES

In the appendix section, three levels of Appendix headings are available.

A.1 General Guidelines (AppendixH2)

1. Save as you go and backup your file regularly.
2. Do not work on files that are saved in a cloud directory. To avoid problems such as MS Word crashing, please only work on files that are saved locally on your machine.
3. Equations should be created with the built-in Microsoft® Equation Editor included with your version of Word. (Please check the compatibility at <http://tinyurl.com/lzzy753> for using MathType.)
4. Please save all files in DOCX format, as the DOC format is only supported for the Mac 2011 version.
5. Tables should be created with Word's "Insert Table" tool and placed within your document. (Tables created with spaces or tabs will have problems being properly typeset. To ensure your table is published correctly, Word's table tool must be used.)
6. Do not copy-and-paste elements into the submission document from Excel such as charts and tables.
7. Footnotes should be inserted using Word's "Insert Footnote" feature.
8. Do not use Word's "Insert Shape" function to create diagrams, etc.
9. Do not have references appear in a table/cells format as it will produce an error during the layout generation process.
10. MS Word does not consistently allow the original formatting to be modified in the text. In these cases, it is best to copy all the document's text from the specific file and paste into a new MS Word document and then save it.
11. At times there are font problems such as "odd" stuff/junk characters that appear in the text, usually in the references. This can be caused by a variety of reasons such as copying-and-pasting from another file, file transfers, etc. Please review your text prior to submission to make sure it reads correctly.

A.1.1 Preparing Graphics (AppendixH3)

1. Accepted image file formats: TIFF (.tif), JPEG (.jpg).
2. Scalable vector formats (i.e., SVG, EPS and PS) are greatly preferred.
3. Application files (e.g., Corel Draw, MS Word, MS Excel, PPT, etc.) are NOT recommended.
4. Images created in Microsoft Word using text-box, shapes, clip-art are NOT recommended.
5. IMPORTANT: All fonts must be embedded in your figure files.
6. Set the correct orientation for each graphics file.

A.2 Placeholder Text

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