Optical Cross Correlation for Similarity Detection

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Abstract

The detection of objects is becoming increasingly important in many applications. Normally, this is achieved on a digital platform, which requires data conversions from the analogue world, combined with many calculations to identify difference/similarity with previously learned objects, such as faces, fingerprints and so on. However, these comparisons can be done much more quickly in the optical domain by using optical wave interference. This requires the object to be stored, which can then be compared with new incoming information through optical wave interference. The strength of the generated signal indicates the similarity between both objects. This paper presents simulation results for such storage and comparisons, including methods to deal with scaling, rotation and other image manipulations, all indicating the successful detection of difference/similarity.

Keywords: cross correlation, Optical wave interference

1 Introduction

Using optical cross correlation for recognition is not new in its own right [1]. However, since its inception there have been significant improvements to optics, while there is also a growth in image processing requirements for a variety of applications.

Some of these applications could be security based, such as fingerprint and/or face recognition, others could e.g. be related to the detection of objects for autonomous driving. In each of these circumstances, a lot of digital computing power is used to perform recognition tasks that could possibly be dealt with in the optical domain. However, this requires the optical solution to be sufficiently robust to noise and other defects, which should be achievable using the correct approaches.

Cross correlation is in itself a sufficiently robust mechanism that allows for a clear distinction between the various comparison results. However, so far, most optical cross correlation systems depend on capturing the optical signal of one of the two signals through a CCD/CMOS camera [2, 3]. The digitised signal is then manipulated using a vast range of digital calculations [4, 5], which often includes a conversion into the Fourier domain. The digital signals are then converted back into the optical domain by using e.g. a Spatial Light Modulator (SLM) [6, 7], which is used to display the signal that was captured by the CCD/CMOS camera. The new input signal is then directed towards the SLM in order to get the optical cross correlation between the two signals. The conversion to the electrical domain is obviously time consuming combined with the many calculations on the digital platform, which, even when parallelised, cannot compare with the full parallelism of working directly within the optical domain. The latter obviously requires developments in the optical domain, but e.g. the Optically Addressed Spatial Light Modulator (OASLM) [8, 9] can only help to progress such developments.

Taking that current digital platforms have not progressed much over the last decades, while the applications they need to perform become increasingly more demanding, it is necessary to exploit other routes of computation, especially if this can be achieved by calculating directly with the incoming signal without any need for conversions. Therefore, this paper presents the development and simulation of a fully optical object identification method that can deal with scaling, rotation and other image manipulations while providing a robust output signal that represents similarity between the input signal and the previously learned object.

2 Methodology and Setup

While the use of cross correlation is a well-known scientific method of identifying similarity, when performing optical comparisons, this would only work well for objects in exactly the same position, which is rarely the case, and so to increase the robustness of the comparison, the objects are compared in the Fourier domain, which is easily achievable in optics through the introduction of lenses. Taking that $a \star b$ denotes the cross-correlation of a and b, $\otimes$ denotes the convolution, and $*$ denotes the complex conjugate, then:

$$a \star b = a \otimes b^* \quad (1)$$

By applying a Fourier transform to both sides, this becomes:

$$F(a \star b) = F(a) . \mathrm{F}(b^*) \quad (2)$$

Then applying the inverse Fourier transform on both sides, results in:

$$a \star b = F_{inv}\big(F(a) . \mathrm{F}(b^*)\big) \quad (3)$$

The optical Fourier transform can be achieved by using a coherent light source with a convex lens of focal length *f* as shown in Figure 1. The Fourier transform of an object placed in front of the lens at distance *f* will then be produced at distance *f* behind the lens. At this position one can then record the object to be recognised in a first, learning, phase, to then use later on. By recording this image in a filter, that allows light through, one can then envision the full setup as shown in Figure 1, where a new object is Fourier transformed onto the special/storage filter, with the resulting correlation being displayed at the detector. At this detector the amount of similarity will be displayed by the intensity of the light, where a higher intensity will correspond to a better similarity between the new and previously learned object.

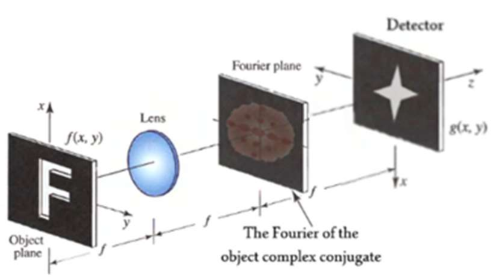


Figure 1. Optical cross correlation using Fourier analysis.

This setup was simulated using COMSOL with one minor alteration. Namely, the convex lens was replaced by a focusing lens (see Figure 2), since if an object is illuminated by a coherent plane wave and the light passes through a focusing lens, then the Fourier transform is reconstructed exactly at focal distance *f* behind that lens [2], which eliminates the need for the object to be at distance *f* before the lens, as required for convex lenses. The simulations were all performed in 2D, resulting in the use of 1D objects, to reduce the overall complexity of the simulations. However, everything demonstrated here, can also be applied using 2D objects in a 3D setting. The input signal is created by modulating a coherent incident wave using a non-reflective material (blue in Figure 2) with a number of air gaps (light blue). The different dimensions of these gaps result in the creation of different input objects.

Each simulation consists of two stages: the first stage stores an object on photographic material located at focal lens distance *f*, to the right of the lens (see Figure 2). The second stage then uses a different object as input. This results in the cross correlation between the signal stored in the photographic plate and the new input which results in an interference which creates a direct indication of the similarity between the input and the previously stored signal.

In real life, objects are rarely at the exact same location or of the same kind when they need to be detected in comparison to when they were learned, and so the system needs to be able to deal with scaling, missing object parts (partial comparisons), noise, rotation and so on, each of which are demonstrated in the next section.

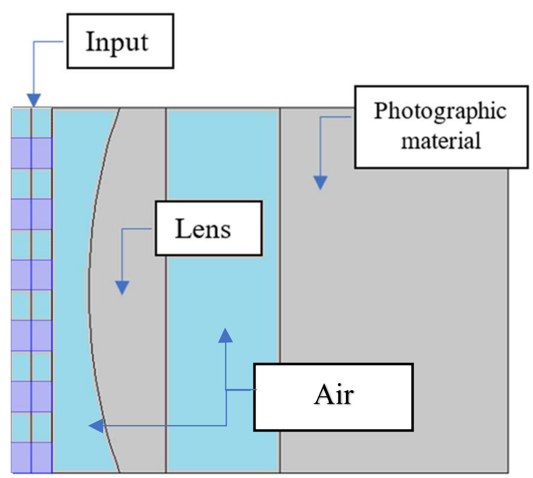
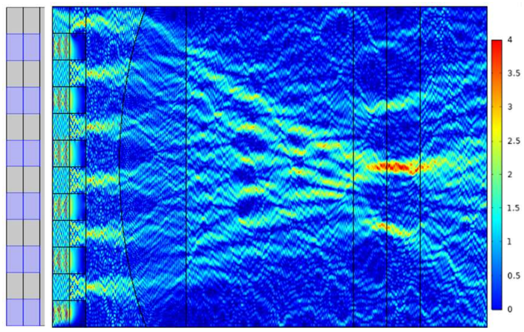


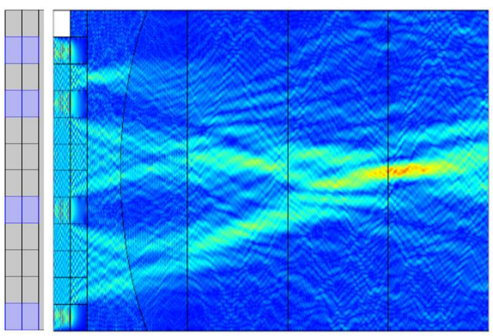
Figure 2. Simulation layout

3 Results and Discussion

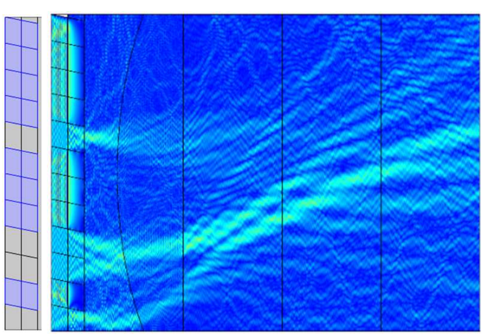
In order to understand the possible range of outcomes of the cross correlation, a number of tests have been conducted which considered an exact match, partial match, and minimised match. The results of these tests are shown in Figure 3. Please note that for all results, the input object is displayed to the left of the electrical field intensity plot for which the scales are all identical and shown to the right in Figure 3 (a). Figure 3 (a) indicates the outcome of a perfect match, meaning that the object to be detected is identical to the one stored (see Figure 2). Figure 3 (a) displays the highest value on the plane that is the focal distance away from the lens (black line indicated on all graphs, positioned in the middle of the photographic material). When one considers Figure 3 (b), which is a partial match, one can notice lower intensity values and even lower values are obtained for Figure 3 (c) which has a quite different input pattern.



(a)



(b)



(c)

Figure 3. Cross correlation results for (a) exact match, (b) partial match, and (c) minimised match.

One should note that due to the objects being one dimensional in combination with the use of the Fourier domain, it is impossible to create a none matching object, as the Fourier transform of the complete opposite object would be the same as a shifted object and therefore simply be recognised as the original object with a slightly lower intensity due to the shifting.

Further simulations focus on comparing the stored object (Figure 2) with a scaled, rotated or partly obstructed version of itself. The results of which are displayed in Figures 4, 5 and 6 respectively.

By increasing the size of the air and non-reflective material gaps, one can simulate a scaled object, and the results for one such simulation are shown in Figure 5. The intensity of the displayed electric field is clearly lower than for an exact match (Figure 3 (a)), but Figure 4 shows a similar pattern at the focal plane, indicating that the object has a very similar pattern and therefore also a similar Fourier transform, which stands in comparison with the objects used to create Figures 3 (b) & (c).

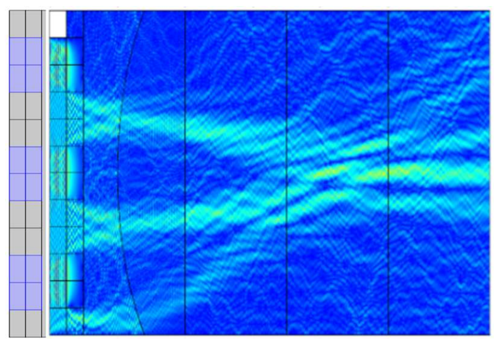


Figure 4. Cross correlation results for scaled object.

Consequently, a good understanding of the created intensity field provides direct information about the object being compared and how it compares with the previously stored information. This could then e.g. be used to identify how the object has been manipulated in comparison to the originally stored image. This can also be seen in Figure 5, which displays the result of an input object that is different from the one in Figure 3 (c), and which consequently produces a different intensity outcome.

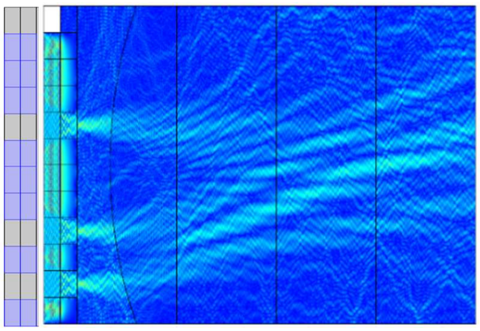


Figure 5. Cross correlation results for object with missing parts.

Similarly, one can look at the intensity field of an object and possibly identify rotation, which can then be used to detect the angle of rotation. Figure 6 shows the simulated result for a rotated image. As to ease the detection of the exact angle of rotation from a set of angles, one can look at the focal length plane only and integrate the intensity values at that plane, which gives an indication of the overall intensity (and matching) at that distance. This can then be plotted for a variety of different angles to identify the exact angle of rotation. An example of this is shown in Figure 7, which indicates the highest peak at the exact angle of rotation.

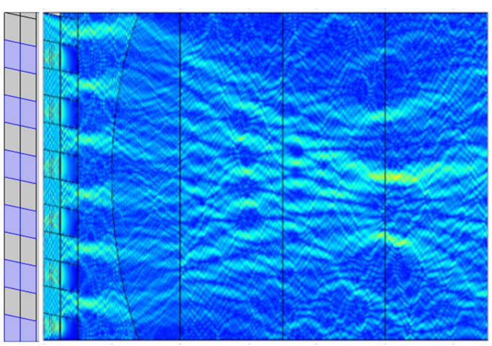


Figure 6. Cross correlation results for rotated object with 22.5°.

In practice one would obviously need to store more than one object, which is perfectly possible when one uses the Fourier transform, as then the positioning of the object is irrelevant to its detection.

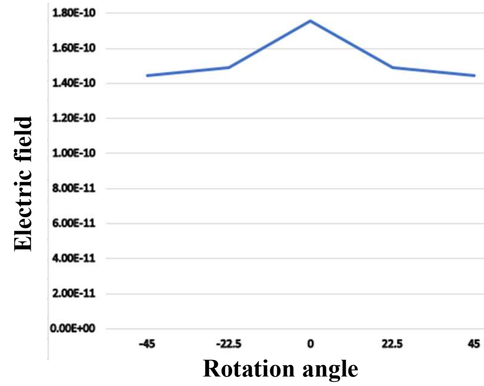


Figure 7. Using integrated intensity values at focal length to identify angle of rotation.

4 Conclusions

The presented simulation results indicate that optical similarity detection is viable and reliable. One can inherently appreciate that a pure optical approach brings substantial benefits in comparison to pure digital/electronic or hybrid optical - electronic systems. Taking the rising importance of image processing and the fact that many signals can be visually represented, there are substantial benefits to being able to process such optical signals directly and efficiently, e.g. for facial and handwriting recognition. While the ability to store objects optically already exists, further improvements in this area are expected that would further substantiate the use of pure optical processing.

Meanwhile this research will focus on improving the interpretation of the intensity pattern and its reflection of the comparison result, as well as how these can be used to identify similarity/difference through e.g. the setting of threshold values. This will then also be expanded into 3D simulations for 2D objects.

Once a sufficient understanding of optical cross correlation has been obtained from various simulations, real optical experiments will be used to further substantiate this approach of optical processing.

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