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A Mach-Zehnder interferometer fringe projector for variable resolution video moiré

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ABSTRACT

A Mach-Zehnder based variable resolution fringe projection system has been built for 3-D video moiré machine vision. This system uses the three main advantages of the Mach-Zehnder - 1) There is no optical feedback to the laser source, 2) The interferometer can accept two different laser wavelengths simultaneously, and 3) The interferometer produces two orthogonal output beams. The lack of optical feedback makes the Mach-Zehnder especially attractive for use with high power laser diode sources which are sensitive to optical feedback. When the two input ports are used with two different wavelength lasers, the target can be illuminated by simultaneous projection of two different sets of colored fringes with two different spatial frequencies. This can allow more reliable reconstruction of the 3-D surface over discontinuous jumps. Finally, the lack of feedback to the source coupled with the dual outputs means that the Mach-Zehnder fringe projector is very efficient in that 100% of the laser light (minus losses in the beam splitters and mirrors) is projected onto the prime and reference targets. Setup and alignment of this interferometer will be discussed for both parallel and diverging light. Plots of fringe visibility will be given for both outputs and both inputs. Application to a video moiré based real time 3-D error map machine vision system will be discussed.

Limitations and improvements in the current system will be discussed.

Keywords: Interferometry, Mach-Zehnder, 3-D inspection, video inspection

1. INTRODUCTION

The use of interferometers as projectors for structured illumination is not a very common practice in spite of the advantage of being able to dynamically vary the spatial frequency of the projected fringes. Unlike a grating or a Ronchi ruling where the spatial frequency is constant for a given source, when using an interferometer one can dynamically adjust the frequency of the fringes without changing the source, optics, or moving the target. By simply tilting or translating a mirror, depending on the interferometer, the number of fringes illuminating a target can be increased or decreased as desired. This ability to change the projected spacing of the pattern is very useful when working with targets of varying size, when there is a need to vary the depth resolution, or when a zoom system is used to examine part of a target at high resolution. The advantage of variable resolution convenience comes at the cost of having to deal with the vibration sensitivity of an interferometer.

In conventional moiré, the projection and viewing gratings are matched physical gratings, and the moiré pattern is the beat between the projection grating distorted by the target and the perfect viewing grating. If the projection rulings are to be surpressed to improve the signal to noise of the moiré pattern, either both physical gratings have to be moved synchronously followed by a video frame average or the optical system must be designed so as to not resolve the gratings themselves (both techniques are used).

Moiré can be achieved in video with a single variable spacing grating projector by splitting the projection beam into a target and matched reference grating, each viewed by a video camera. The moiré pattern is generated by mixing the video signals from the target camera and the reference camera, typically by using a Chroma-key circuit[1]. Splitting the structured illumination is very important because it insures that the pattern illuminating both the target and the reference are identical. The output of any interferometer can be split with a beamsplitter, but the optical power on each surface is halved, after the

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losses in the beamsplitter are taken into account. To achieve the synchronously moving gratings it is necessary to translate one of the interferometer mirrors, but the beamsplitter assures that both the reference and target fringes move together.

Most interferometric fringe projectors use Michelson interferometers[2,3,4,5], but a recent paper reports the use of a Mach-Zehnder[6]. The Mach-Zehnder interferometer is well suited as a projector for structured illumination. The interference pattern generated by the interferometer can easily be adjusted either by tilting or by translating a mirror or beamsplitter to produce any spatial frequency desired, and the interferometer will work with either a parallel or a diverging beam. The Mach-Zehnder automatically produces the two matched fringe patterns required for video moiré profiliometry[1,2,7]. In addition, the Mach-Zehnder does not reject half of the light back to the source at the first beamsplitter as the Michelson does. For many types of laser sources, the lack of optical feedback to the source is a major advantage. Ignoring losses in the beamsplitters, to our knowledge the Mach-Zehnder is the only 100% efficient two beam fringe projector, since physical gratings or Ronchi rulings absorb half of the light and the Michelson rejects half of the light back to the source. Finally, the Mach-Zehnder can be simultaneously illuminated by two different lasers, allowing some unusual applications, including two color interferometry.

Another characteristic of the Mach-Zehnder interferometer, which can have both advantages and disadvantages, is that the two interference patterns are 180° out of phase relative to each other. Referring to Figure 1a, if one examines the output beams, using R for the reflection and T for the amplitude transmission coefficients, the output parallel to the direction of the input beam is RRT + TRR, while the perpendicular output is RRR + TRT. The same result is obtained for the second, perpendicular input, as shown in Figure 1b. The perpendicular output beam is asymmetric in R and T and may have too much optical path difference for optimum contrast fringes - the standard Michelson solution of inserting a tilted phase plate in one beam will not work here. Even if the second output has reduced fringe contrast, it is still suitable for a reference beam. In one of our experiments with a pair of new beamsplitters we discovered that the RRR + TRT beam did not generate interference fringes, while the other beam did. This problem was traced to a mis-shipment of polarized beamsplitters and when they were replaced with non polarizing ones, both interference patterns reappeared.

2. POSSIBLE CONFIGURATIONS AND APPLICATIONS

First we will discuss possible configurations for the interferometer and then suggest several applications related to machine vision. The first consideration is whether the interferometer will be set up with an expanding beam (Figure 2a) or with parallel light (Figure 2b). Providing the expansion angle is large enough, the expanding beam setup minimizes or eliminates optical components following the interferometer, but requires the interferometer optics to be large enough to avoid vignetting the expanding beam. Note that in both Figures 2a and 2b, a spatial filter and additional optics are used to clean the beam and either make the beam expand slowly enough to pass through the interferometer optics (Figure 2a), or make the beam parallel in the interferometer, possibly followed by additional external optics to expand the beam to cover the target (Figure 2b). The expanding beam configuration is also easier to understand from a theoretical standpoint, being basically a complex embodiment of the classical Young's two-slit experiment. In operation, the rotation of one mirror or the translation of a mirror or beamsplitter perform the same function - moving either changes the spatial frequency of the fringes, and with about the same sensitivity. At the high spatial frequencies used for structural illumination, the curvature of the fringes is minimized, and a small rotation or translation of a mirror or beamsplitter can be used to shift the fringes for multiple image capture for 3-D reconstruction or to remove the fringes themselves by frame averaging, leaving only the moiré patterns for video moiré. The slight change in spatial frequency during fringe shifts is not a problem at high spatial frequencies, since the three or five shifts between frame captures total one fringe shift. When the mirror is tilted to change the spatial frequency, beam steering reduces the region of interference, causing the projected beams from the two arms of the interferometer to diverge. Beam steering appears to be minimal at the high spatial frequencies, but the fringe curvature is slightly more than in the comparable parallel beam setup.

The parallel beam setup uses a spatial filter and beam expander to clean the beam and make it parallel before the interferometer as well as additional optics following the interferometer to expand the beam. This additional beam expansion is not necessary if the parallel beam in the interferometer is large enough to illuminate the target. However, a system without a following beam expander would not be easily adaptable to a wide range of target sizes. The spatial frequency of the fringes can be changed by rotating one mirror about the vertical axis, and the fringes can be scanned or shifted by translating one of the beamsplitters. This fringe shifting does not appear to cause any significant change in the fringe spatial frequency, and the translation of the beamsplitter appears to be much less sensitive that that in the expanding beam interferometer, which should make precise control of the shifts easier. The parallel beam system appears to have less fringe curvature and less beam steering than the expanding beam interferometer.

In both the parallel and expanding mode of operation, the second input is available for use with a second wavelength laser, allowing two color interferometry which can lead to more reliable 3-D reconstruction of surfaces[8]. A major feature of the Mach-Zehnder, the two output beams are ideal for use as fringe projectors in video moiré. As shown in Figure 3a, one output beam illuminates a target and the other illuminates a reference plane, each viewed by a video camera. When the two video signals are mixed using a Chroma-key circuit, real-time video moiré equal depth contours result[1,2]. If a perfect target surface is substituted for the reference plane as shown in Figure 3b, error map contours[7] between the perfect target and the reference are seen. In the error map mode, the optical trains in both target and reference beams and target and reference cameras must be identical to ensure 1:1 depth calibration, but it is possible to use a scaled (usually smaller) reference surface providing the projection and viewing optics are also scaled. Other applications include determining the intersection of two arbitrary surfaces in real time[9], and a setup using two identical targets which generates contours proportional to the misalignment of the two targets, which could be used for robotic assembly or alignment for automated spacecraft docking.

3. ALIGNMENT

The Mach-Zehnder interferometer has a reputation for being more difficult to align than other 90° interferometers such as the Michelson, but perhaps not as hard as the "oblique" interferometers, such as the Sagnac. We have developed a modification of one of the standard Michelson alignment techniques that speeds the process.

1) Position and level a laser with an unexpanded beam along one of the input directions.

2) Square the first beamsplitter to the optical axis by aligning the beam reflected off the beamsplitter front surface with the exit hole of the laser.

3) Roughly align the mirrors by checking that the reflected beams stay at the same height as the input beam and track perpendicular and parallel to the original beam over a long distance (1-2 m). This is easier to do if the input beam is aligned with one of the rows of holes on an optical table.

4) Align the second beamsplitter so that the two beams coming from the two mirrors cross in the center of the that beam splitter. Then rotate the beamsplitter so the two sets of beams now coming from the beamsplitter form one dot at each output, created by the overlapping of each set of beams.

5) Translate one of the mirrors along an axis of the interferometer to cause a separation of the beams. Check one output to see if the two beams maintain the same separation over a reasonable distance (1-2 m). If they do then the instrument should be aligned properly, but there will not be interference since the beams are not overlapping.

6) If the separation distance between the two beams increases or decreases, adjust the second beamsplitter until the two beams remain parallel. If the beams cannot be made parallel by adjusting the second beamsplitter, then repeat steps 3 on.

7) Reduce the separation of the beams by reversing the mirror translation performed in step 5 until the beams overlap. At this point the rough alignment of the interferometer is complete and the final alignment can be performed.

8. Turn off the laser, and insert a test target between the laser and the interferometer. Use a piece of white paper with a fine black cross drawn on it or make a cross on the paper with narrow black chart tape. As an alternative, place a wire grid in front of a back illuminated ground glass plate. Using either your eye or video camera with a lens focused on the cross, make fine adjustments of mirror tilt and possibly translation until the two images of the cross coincide.

9. Remove the alignment target and install a spatial filter and beam expander set for either a parallel or an expanding beam.

10. Only fine adjustments of the mirror and beamsplitter should be necessary to project interference fringes. On the parallel beam setup, tilting either mirror slightly about its vertical axis will change the spatial frequency of the fringes, while translating the beamsplitter will shift the fringes. On the expanding beam setup, either tilting the mirror or translating the beamsplitter will change the fringe spatial frequencies.

4. FRINGE VISIBILITY AND SPATIAL FREQUENCY

As mentioned in Section 1, one of the output beams is asymmetric in the reflection and transmission coefficients - which output depends on which input is used. Referring to Figures 1a and 1b, the output that is parallel to the input is symmetric (the beams are RRT and TRR), while the output that is perpendicular to the input is made up of beams that are asymmetric (RRR and TRT). There was a concern that although approximately 50-50 beamsplitters were used, there might be a difference in fringe visibility between the two outputs. A series of experiments was conducted to see if this could be a problem. An expanding beam Mach-Zehnder was set up with the fringes projected onto two CCD video cameras, one at each output. For each camera and each input, as the beamsplitter was translated to change the optical path length, the fringe visibility (fringe contrast) of the captured image was measured, and the number of fringes in each field of view were counted. As expected, the fringe spatial frequency increased linearly with beamsplitter displacement, from approximately 3 c/mm to 23 c/mm as the beamsplitter was translated approximately 2.5mm (Figure 4). At the same time, as seen in Figure 5, the fringe visibility decreased from approximately 95% at a mirror displacement of 0.05 mm to as low as 20% at 3 mm. The fringe visibility remained above 80% out to a displacement of 2.5 mm (parallel output) and 2 mm (perpendicular output), verifying the assumption that the asymmetry in the perpendicular output would reduce the fringe visibility. The falloff in fringe visibility with large beamsplitter displacements is due to the extreme optical path difference (3 mm is on the order of 5400 wavelengths). In actual operation, to shift the structured illumination one total fringe the beamsplitter translation required is on the order of one wavelength. From a beamsplitter displacement of 0.0 mm to 0.6 mm, the fringe visibility was essentially constant for both outputs (between 98% and 93%). Because of the noise in the dark regions of the captured CCD image, there is about a 15% uncertainty in the higher values of fringe visibility. From a practical standpoint, adequate fringe visibility for machine vision was achieved in both outputs. Higher spatial frequency projected fringes can be easily achieved by rotating one of the mirrors, but in the experiments reported here the spatial frequency was limited to ease the measurement process. Similar experiments were performed with the interferometer in the parallel beam configuration with comparable results, except that the fringe spatial frequency was varied by rotating one mirror, which was harder to quantify.

5. CONCLUSIONS

For machine vision applications requiring the projection of variable spatial frequency structured illumination, the interferometer is the projector of choice. In situations where two matched structured light outputs are needed, such as video moiré, the Mach-Zehnder interferometer provides both beams with near 100% efficiency - there is no loss out the back of the interferometer. This lack of a reverse path beam means that there is no optical feedback to the source, an important advantage when laser diodes are used. The Mach-Zehnder can be operated with two independent monochromatic sources simultaneously, generating two sets of fringes with different colors and spatial frequencies, which has advantages in the reconstruction of 3-D surfaces. As with the Michelson interferometer, the Mach-Zehnder allows precise fringe shifting independent of the adjustment of the fringe spatial frequency. For these reasons, the Mach-Zehnder interferometer can be an excellent choice when variable spatial frequency structural illumination is needed.

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7. FIGURES

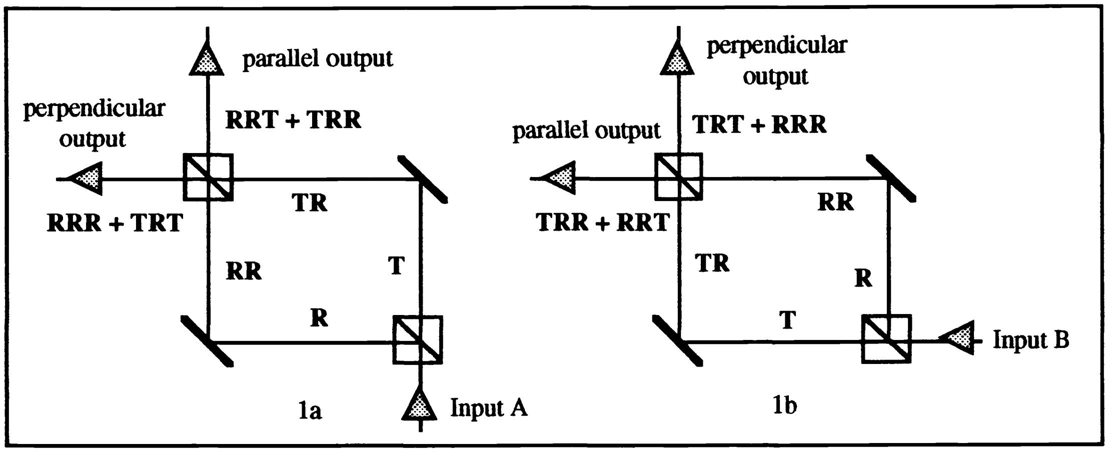

Figure 1: Transmission and Reflection Coefficients of Mach-Zehnder Interferometer: 1a: Input A, 1b: Input B

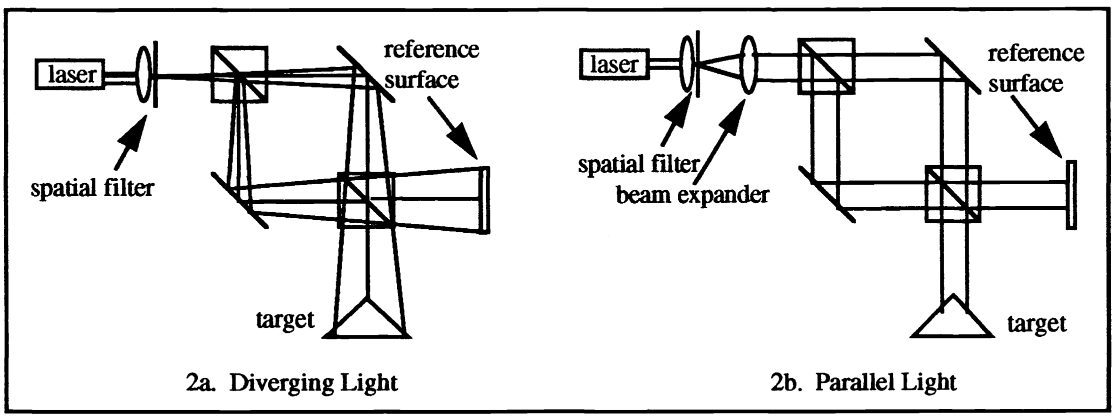

Figure 2: Mach-Zehnder Interferometer set up in: 2a: Diverging Light, 2b: Parallel Light

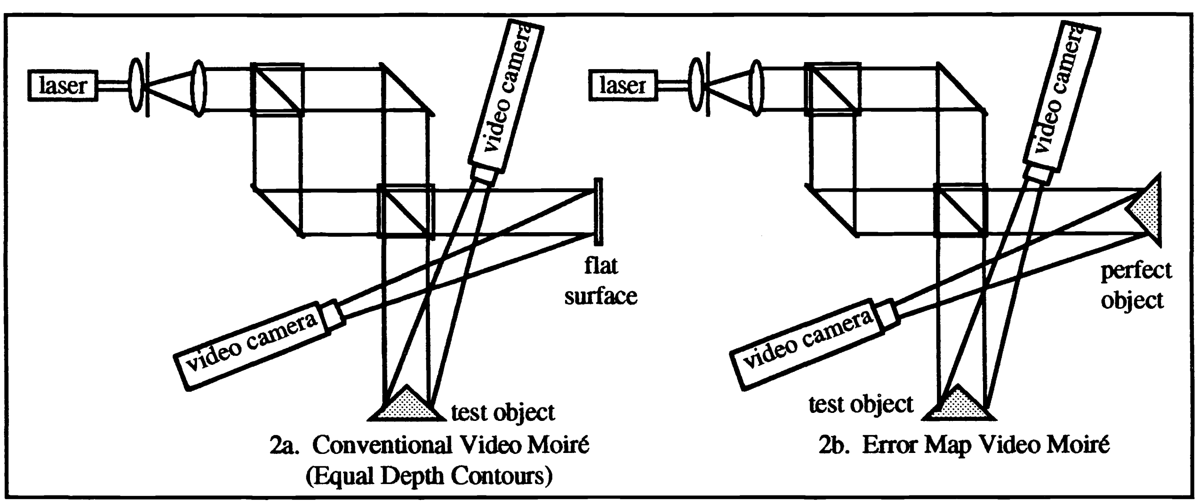

Figure 3: Applications of Mach-Zehnder to Machine Vision: 3a: Conventional Video Moiré (equal depth contours), 3b: Error Map Video Moiré.

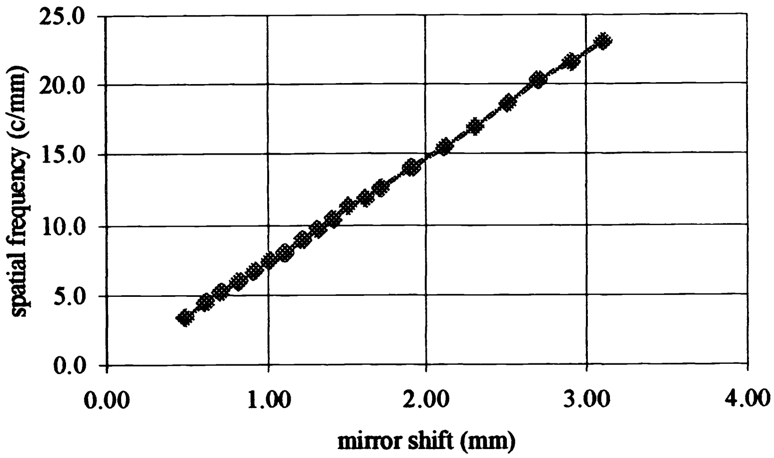

Figure 4: Fringe spatial frequency vs. mirror displacement.

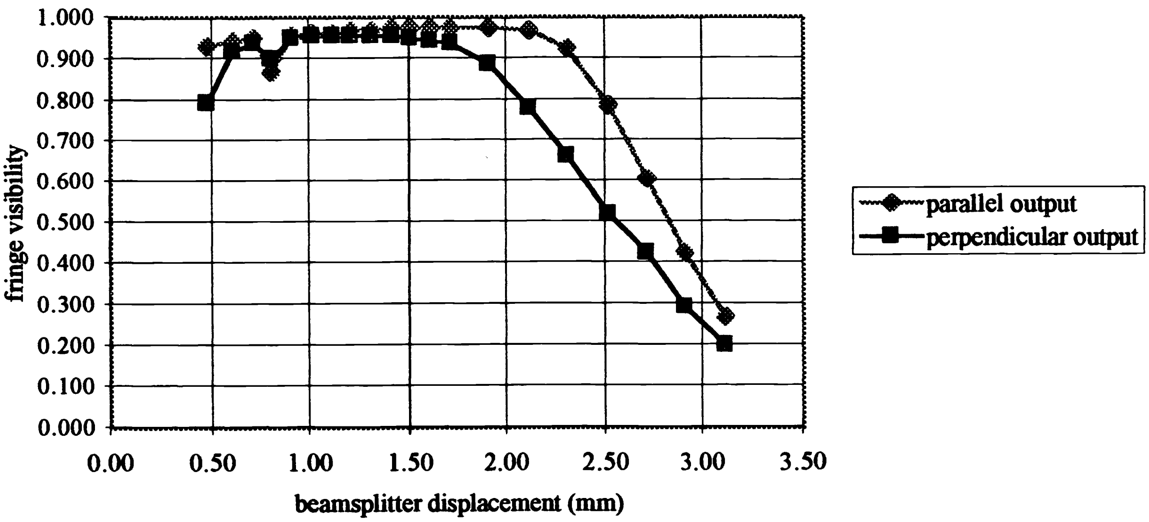

Figure 5: Fringe visibility vs. beamsplitter displacement.