Title of the CMSC White Paper: Virtual Inverse Fringe Projection
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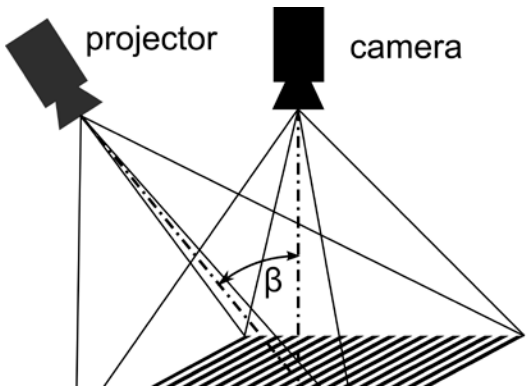
Abstract: Geometric measurement is essential to guarantee function and quality of a huge variety of goods. Fringe projection (FP) has been well-established as a three dimensional measuring technique but lacks speed performance for in-line use. Inverse fringe projection (iFP) is a modification of the FP principle that can meet significantly better performance criteria but is very uneasy to setup. Our proposed virtual inverse fringe projection system provides a method to overcome the setup difficulties of iFP by means of computer simulation techniques and prepares iFP for broader application.

1 Introduction

Industrial quality management requires the inspection of semi-finished and finished goods with respect to their geometric shape. In most cases an ideal workpiece geometry is known from CAD-data (computer aided design) and the maximum allowed deviation from the ideal geometry is specified.

Whilst simple mold workpieces can be measured efficiently by conventional methods, such as contact-based methods, complex free-form designs are much more difficult to measure. Free-form surfaces require high resolution measurement of their entire surface shape, which is an impracticable task for contact based or non-contacting methods that produce single point measurements.

2 Conventional Fringe Projection



Fringe projection (FP) has been established as a prevalent “areal” measuring technique, which is economic, flexible and non-contacting. Conventional fringe projection works by projecting structured light patterns – mostly fringes with a specific spatial carrier frequency – onto the optical cooperative surface of a three dimensional workpiece. When the diffuse reflexions of these patterns are recorded by a digital camera that has an optical axis drawing an triangulation angle β to the projector's optical axis (see figure 1), distorted patterns can be observed which allow for the reconstruction of the object's three dimensional shape by means of the triangulation principle. In order to gain sufficiently reliable and unambiguous data to rebuild the complete object geometry, several distinct fringe patterns with different spatial frequencies and phases need to be projected and

analyzed [1]. The object's shape is obtained as a three dimensional point cloud that needs to be filtered for artefacts, polygonized and fitted into the CAD model of the workpiece in order to determine defects and geometry deviations.

However, especially polygonizing and model fitting are very time consuming tasks for state-of-the-art computers. The multi pattern projection and image acquisition procedure can be expected to take several seconds or more. The overall inspection time including data processing can be expected to take up to a few minutes which is way too much for the majority of applications, such as in-line inspection in particular.

Commercial conventional FP systems are available in different scales for measurement of workpieces with an overall size of a few millimeters up to several meters and show the flexibility of the FP principle.

3 Inverse Fringe Projection

Inverse fringe projection (iFP) is a variation of the FP method that is capable of utilizing one single special projection pattern, which is adopted to the workpiece geometry as well as the total system setup, for measurement of a workpiece's deviations from the ideal shape without need for the computational expensive steps of polygonizing and model fitting. This *inverse projection pattern* is designed with the constraint that a flawless workpiece responses into undistorted straight line patterns in the camera image (quite the opposite of conventional FP) and workpiece defects result, then, in a distortion of the straight lines in the camera image (see figures 4 and 5). As the occurrence and characteristics of straight line distortions can be computed very efficiently and very robustly, a fast and reliable defect detection procedure can be implemented without handling 3D data structures in the inspection process at all. The computational effort for defect analysis is therefore reduced to a two dimensional image analysis problem which can be solved efficiently by well-established algorithms.

However, there is barely any iFP system in application nowadays because generation of the inverse fringe pattern has been a very costly procedure that requires a seamless master workpiece present in the measurement setup as well as an uneasy procedure of canceling out fringe distortions in the camera image by variation of the projected pattern until the desired straight lines are observed [2]. Any changes in the system setup, be it, for example, replacement of the projectors light bulb, slight camera displacement or redesign of the workpiece, necessitate repeating the whole procedure.

4 Virtual Inverse Fringe Projection

We propose a new method of obtaining the inverse fringe projection pattern by the help of *virtual* fringe projection without any need for a master workpiece or physical system access. The key part of our method is reversing the light path via raytracing computer simulation in order to compute the correct *inverse fringe pattern* directly.

Raytracing is a widely used method in computer graphics to calculate the mapping of a three dimensional scenery onto the pixel sensor of a digital camera respecting scene illumination with the virtual model complexity (and accuracy) solely limited by the computational resources. For further information on raytracing methods the reader is referred to the literature [3].

For generation of inverse fringe patterns and for the purpose of investigating the iFP method, we

have written our own raytracing simulation software. The computer program allows us to virtually assemble a complete (inverse) fringe projection system consisting of established models for pattern projectors and cameras with the capability to import CAD models of three dimensional workpieces. With this virtual setup the software can raytrace forward and reverse light paths by virtually exchanging camera and projector. Hence, we can calculate the related *inverse projector pattern* for any arbitrary desired camera image concerning a workpiece's CAD model (see figure 2). Taking into account the constraint of section 3, that the camera image should render straight fringe patterns, our raytracing software can generate the *inverse fringe projection pattern* (figure 3).

As the total system setup influences the characteristics of the inverse fringe pattern, all system parameters of the setup must be known before calculation, that includes optical projection parameters of projector and camera (namely extrinsic and intrinsic calibration matrices) as well as optical distortion coefficients [4, 5]. However, conventional FP requires exactly the same type of calibration procedure and adequate procedures are established. The only additional constraint of the iFP method over conventional FP is that the workpiece positioning must be known *a priori*. Precise workpiece positioning can be ensured either by mechanical clamping or adaptive fine positioning by the help of the already present FP system camera [6].

Furthermore our software allows us to apply the generated inverse fringe pattern to the virtual scenery by the virtual projector and simulate the resulting camera image, which is expected to be similar to the camera image of a real measurement procedure. This way we can easily obtain a huge database of various geometry defects and their characteristics under the inverse fringe projection (see examples in figures 4 and 5).

Figure 3: Visualized CAD model of an airplane turbine impeller blade

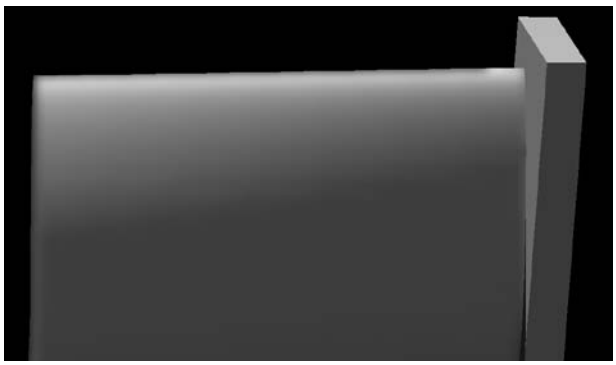
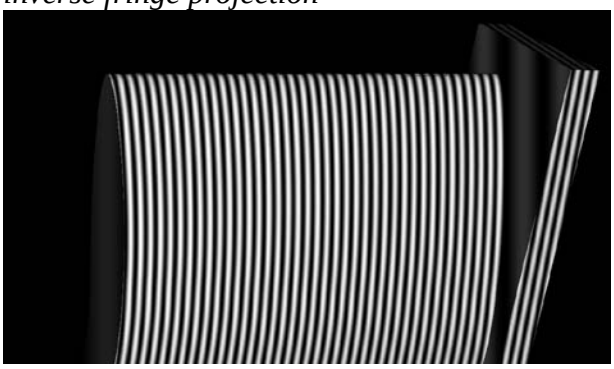


Figure 2: Inverse fringe projection pattern of impeller blade, calculated by the virtual inverse fringe projection



5 First Results

Figure 4: Virtual application of the inverse fringe projection results in straight

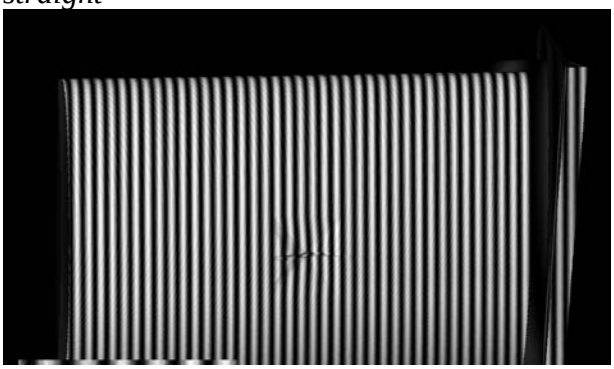
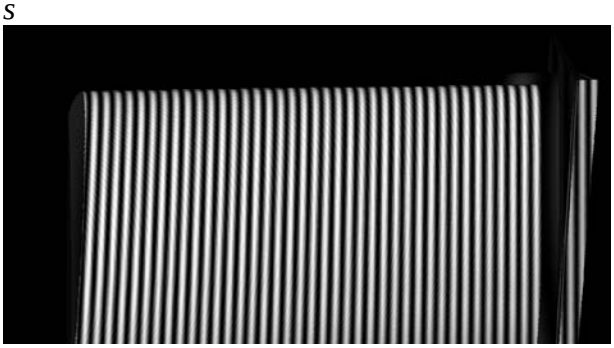


Figure 5: Virtual application of the inverse fringe projection results in non-vertical skewed lines (left hand s



Preliminary results show that the inverse fringe pattern can be accurately calculated by our software and applied to the complex geometry of a free-form workpiece, namely a turbine impeller blade. (Note: For legal reasons, a purely fictive impeller blade model is used for all images throughout this paper.) As expected, the virtual fringe projection system is capable of accentuating local defects as well as global deformation of the workpiece with respect to its ideal shape.

Local workpiece defects (scratches or dents, for example) emerge as local distortions of the otherwise straight lines in the camera image. At the defect locations in figure 4 the vertical fringes experience local curvature and horizontal displacement. The amount of curvature/displacement is related to the geometry of the workpiece defect. In the example even a tiny scratch visualizes as a significant distortion in the fringe pattern.

Global defects such as twists of the whole workpiece geometry result in a dislocation and skew of the observed fringe lines in the camera image. Without the enormous computational efforts of three dimensional polygonizing and model fitting algorithms, is it possible to detect the global twist of the turbine impeller blade in figure 5. Taken together, a great span of possible geometric workpiece defects can be en-visualized by the iFP that utilizes the inverse pattern generated by our virtual fringe projection system.

An additional feature that iFP provides over conventional FP is that workpiece defects are intuitively detectable in the resulting camera image by human individuals and permit facile human supervision over an automated measurement system.

6 Conclusion

We presented a method to efficiently calculate the required inverse fringe pattern for an iFP system. This method can give the inverse fringe projection method a push into application for fast three dimensional measurement of complex shaped optical cooperative workpieces. Using this system local defects, dents or scratches for example, can be detected as efficiently as global defects. Especially the latter feature highly excels conventional free-form 3D measurement systems.
The system has a potential for application in mass production lines as well as in single part production because of its high flexibility to varying inspection goods due to the fact that all workpiece depended data can be prepared in advance and loaded quickly by software. A multi camera/multi projector iFP setup can be developed straight forward in order to implement a quick full part inspection system. The principle of iFP is, just like conventional FP, scalable to workpieces with an overall size of few millimeters to several meters.
As the hardware requirements do not cover more than a standard DMD-based projector, a standard

industrial camera, both with appropriate off-the-shelf optics, and a state-of-the-art computer, the acquisition costs of the system are in an attractive magnitude for many applications; already installed DMD-based conventional fringe projection systems could be software upgraded.

7 Future Work

We carry on developing a mathematical model of the inverse fringe projection system that allows for precise metric quantification of workpiece shape deviations directly out of the iFP camera image. From this mathematical framework we plan to investigate the resulting uncertainty in measurement and are researching methods to efficiently cope with the problem of imprecise workpiece positioning.

8 Acknowledgments

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