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Fringe Projection Simulation Software for 3D Shape Measurements

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Abstract:

Profilometry with LCD or DLP beamers has become a common three-dimensional scanning technique[1]. Many attempts are made to enhance the accuracy of these measurement systems, by developing new algorithms or improving the existing ones. Comparing these algorithms to the existing methods requires building a validation setup. This validation setup has to be carefully calibrated to obtain realistic measurement data. Additionally the distortions of the different components need to be compensated. Building these setups often takes a lot of valuable research time while the goal of many research projects is to improve the mathematical fringe analysis tools without having to deal with practical problems of a test setup. This paper presents the 'Fringe Projection Simulator', a program which can simulate three commonly used fringe projection setups. All three setups contain a beamer and a camera with a diverging lens. The program is available for download free of charge at: http://www.fringesimulator.com.

Introduction

Three-dimensional measurements have become a common quality control technique in modern factories. Different measurement time requirements have lead to the development of different techniques such as laser line scanning, grid projection and Moiré profilometry. Within the group of fringe projection techniques a subdivision between spatial and temporal methods can be made. The software presented in this paper can simulate both methods, which allows you to compare their results.

Validation of three-dimensional scanning techniques can be time consuming and strenuous because a small error in the setup can lead to large errors in the measurements. Various factors such as the distances between the components, the surface quality of the object and lens distortions can affect the results tremendously. Therefore, if the results do not meet the expectations, discerning the cause can be very difficult. This task would be made much easier by simulating the results first. Performing simulations the traditional mathematical way is possible if the objects are not too complex. Creating complex objects with mathematical software is time consuming. The 'Fringe Projection Simulator' however, is designed to support STL files. This enables the user to create a 3D model using any CAD program.

Additionally, the 3D drawings can be used for computer-aided manufacturing of the object. This allows for a more efficient validation with real life setups afterwards. For the optimization of the setup parameters, an existing software tool can be used [2].

Fringe projection technique

Calculating a heightmap of a 3D shape requires several key steps (Fig.). The first step is generating the sinusoidal fringe pattern that will be projected on the object and the reference plane. The intensity image of the sinusoidal fringe pattern projection

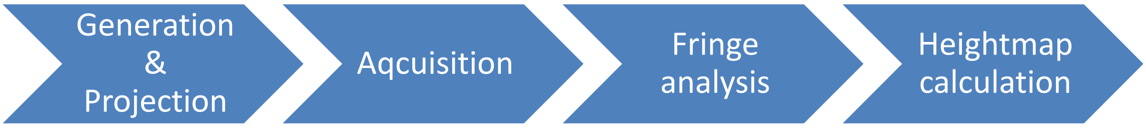


Fig. 1: Fringe projection profilometry flow chart

on a plane, as captured by the camera, can be expressed by

where is the background intensity, the fringe modulation, and is the phase value. To extract the phase , either a spatial or temporal analysis technique can be used. It's important to choose the right algorithm for each measurement, as both methods have specific advantages and disadvantages when it comes to dealing with small or large height steps. The key task for the analyst is to find that combination of setup and technique which results in optimal accuracy. When using spatial methods, a sufficiently high frequency carrier (Fig. 3) is required to perform a qualitative measurement. Temporal fringe analysis uses multi-step techniques [3] or techniques with increasing frequencies [4].

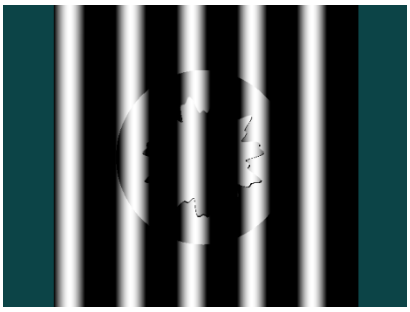


Fig. 2: Object with low spatial carrier

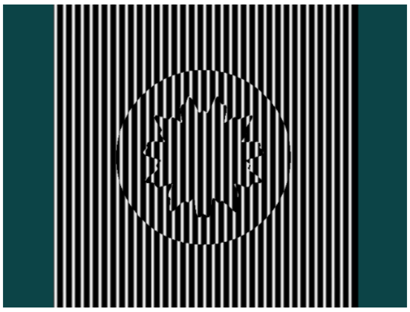


Fig.3: Object with high spatial carrier

After the phase is extracted, an unwrapping algorithm has to be used. If this step is successful, the correct phase is found in all the pixels of the image.

Camera calibration is used to find the relation between the phase values and the real world coordinates. When using ideal lenses in an off-axis setup, the relationship can be determined using simple triangulation, as described in this formula:

$$h(x, y) = \frac{l_0 \Delta\phi(x, y)}{\Delta\phi(x, y) + 2\pi f_0 d}$$

where l_0 represents the distance between the parallel plane, in which the projector and the camera are positioned, and the reference plane of the setup. The distance between the camera and beamer pupil is given by parameter d. When the carrier is removed, the objects shape-related phase component $\Delta\phi(x, y)$ is left.

In real life however, it is nearly impossible to measure d and l_0 accurately. Instead, these parameters are calculated during the calibration procedure. Unfortunately, these procedures are time consuming and introduce a measurement error as well. A simulation on the other hand, in which d and l_0 can be defined by the user would be much more accurate and could also be very helpful in determining the influence of every parameter.

Different setups

Various beamer projection setups can be found in the literature. The difference between these setups lies in the alignment of the beamer and the camera to the reference plane. The following three setups are supported by the software described in this paper.

In the first setup (Fig. 4), the beamer is perpendicular to the reference plane and the camera is placed at an angle α. This makes the relation between the camera pixels and the real world coordinates more difficult to calculate. Therefore thorough camera calibration is needed here and knowing the exact position of the camera is essential to calculate the correct X and Y coordinates. This can lead to a large measurement error, which is why setup 1 is used the least.

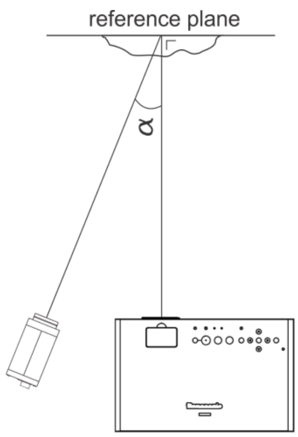


Fig. 4: Setup 1

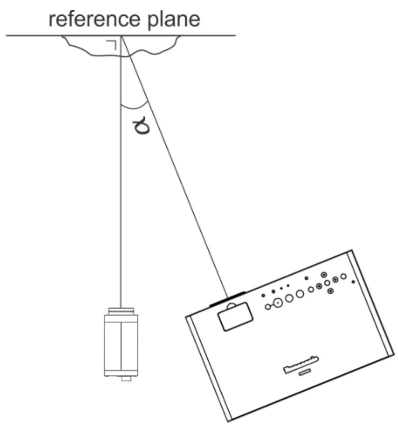


Fig. 5: Setup 2

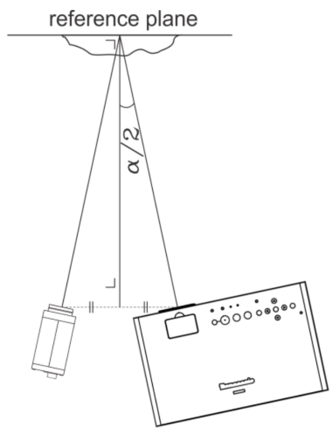


Fig. 6: Setup 3

In setup 2 (Fig 5), the camera is perpendicular to the reference plane and the beamer is placed at an angle α. The main advantage over the other setups is that the relation between real world coordinates and camera pixels is straightforward which leads to a smaller measurement error.

Lastly, an off-axis measurement setup (Fig. 6) can be used. Both beamer and camera are positioned at an angle α/2 to the reference axis. In most cases the camera and the beamer are placed at the same distance of the reference plane, however the software allows you to determine each distance separately.

Supported features

Camera parameters

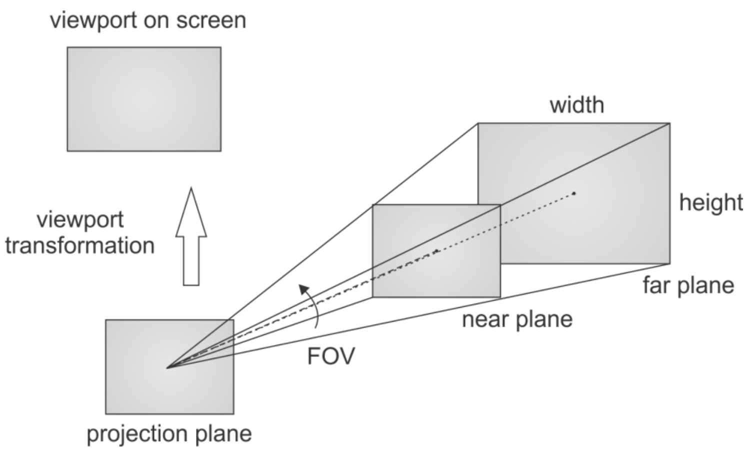


Fig. 7: Camera parameters

In the software, the camera is defined by two coordinates and four parameters (Fig. 7). The first important coordinate $C(x, y, z)$ is the location of the pupil of the camera. The second coordinate is the target $T(x, y, z)$ at which the centre of the camera is aimed. In most cases this will be the centre of the object you want to measure.

The first two parameters are the 'near plane' and the 'far plane', which define the beginning and the end of the visualized area. Anything located in front of the 'near plane' and behind the 'far plane' will not be visible. The camera angle is defined by the field of view (FOV) parameter in the software. Being able to adapt this parameter is incredibly helpful in determining which optical components are ideal for building a new setup. The fourth parameter is the 'aspect ratio' of the camera, which defines the relation between the width and the height of the view.

Beamer parameters

The location of the beamer can be determined by the user, but the software automatically assumes that the beamer is pointed to the middle of the 3D shape. The other parameters describing the beamer are the 'angle' of the beamer lens and the 'aspect ratio', which are similar to the corresponding camera parameters.

Spatial and temporal measurements

The presented 'Fringe Projection Simulator' software is designed to simulate both spatial and temporal situations. When using spatial measurements, the frequency can be set by the user. A straightforward menu allows you to set the phase shift by selecting one of the standard values or by entering a specific value. Clicking the 'take single shot' button simulates taking a picture with the camera and stores it at the chosen location. This way, shots using specific frequencies and phase shifts can easily be made.

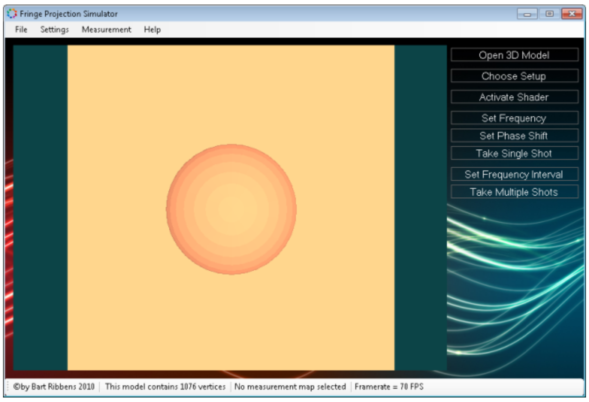
Taking multiple shots while increasing the frequency is possible by entering the starting frequency, the stopping frequency and the number of steps to be taken. The same is also possible for an increasing phase shift, which makes it easier to evaluate temporal phase shifting techniques. In this case the frames will be generated using the highest speed possible. This speed is determined by the power of the CPU and the graphics card of the user's computer.

Shadows

An important improvement of this simulation software over other mathematical simulations is that by using 3D models natural shadows will appear in the images. This means that no phases will be calculated in places the light of the beamer can't reach. Regular mathematical simulations do not account for shadows, therefore the simulated results will nearly always be more accurate than those of real experiments.

Demonstration

To serve as a test object, a sphere is created in Autodesk 3ds Max and exported as an STL-file. This file is opened in the 'Fringe Projection Simulator' (Fig. 8) and a fringe projection with a frequency of 20 lines/reference plane is applied (Fig. 9).



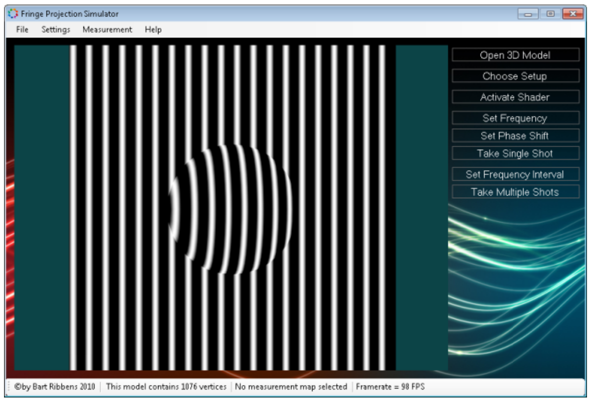


Fig. 8: Sphere without projection

Fig. 9: Sphere with fringe projection

By using a common four-step phase shifting technique, followed by a phase unwrapping algorithm, a heightmap can be calculated [5].

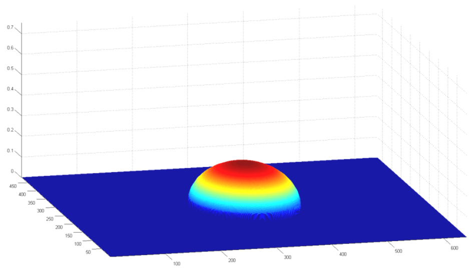


Fig. 10: Calculated height map

Conclusion

The 'Fringe Projection Simulator' can be a valuable tool in the validation process of new or improved fringe projection algorithms. It saves you time by generating baseline data to compare with real life measurements, or by allowing you to bypass a real life setup entirely.

Since all parameters are known, no time is wasted searching for errors in the setup that may have influenced the results. Finally, the program allows you to import 3D models which generate realistic shadows, as opposed to mathematical simulations.

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