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Shape verification aimed for manufacturing process control

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ABSTRACT

We describe a method to verify the shape of manufactured objects by using their design model. A non-contact measuring method that consists of a stereo-camera system and a single projected fringe pattern is used. The method acquires one image from each camera. Additional shape information from the design model is also used. This surface-measurement method gives an accuracy of about 45 μm. Deviations from the design model within ± 1.6 mm can be correctly detected. The measured surface representation is matched to the design model using the ICP-method. Fast performance has been considered adapting the method for on-line use.

1. Introduction

We consider the computer vision problem of measuring the shape of an object and compare it to its design model. The aim of the work is to adapt both the measurements and the analysis for on-line measurements of a large number of identical components in the manufacturing industry. Hence, the computer vision process must be fast and reliable. The measurement of the shape results in a large number of object points representing the surface of the object. The object points are fitted onto the surface of the design model, which is represented in a CAD system.

As described in [1] there are two principal techniques for measuring the shape of an object; contact measurement and non-contact measurement.

Contact measurements are normally done using a pre-produced measurement jig or a coordinate-measuring machine (CMM) [2–4]. The non-contact measurements are usually done using optical methods. Different optical methods and some of their applications are described in [5–7].

Compared to a CMM the optical methods are usually fast, often because they can measure several points, i.e. full-field, at once. Depending on the choice of measurement technique the measurements can also be robust and accurate. We have chosen to work with a stereo camera system together with a projected fringe pattern. A stereo camera system is based on optical triangulation which is a measurement principle known to produce reliable results with positional accuracy of the order of 0.1 mm, which is sufficient for most manufactured parts. The system basically works like the stereoscopic vision of humans and relies on the presence of features on the object that can be seen by both cameras in order to connect them with each other. In our work the projected fringe pattern becomes these features, hence the system is active [8–10]. The choice of a continuous projection pattern like sinusoidal fringes makes the accuracy and resolution of the system high. Recent reviews of real-time shape measurements with projected fringes and its pros and cons can be found in [11,12].

There is an inherited problem with the use of a fringe pattern wherein a wrapping problem appears that prevents the measurement of discontinuous objects. A common solution to this problem is to use a temporal sequence of different patterns, which tends to be time-consuming and prevents the measurement of moving objects. In the literature different methods have been introduced to make triangulation measurements faster, e.g. by using high speed cameras [13] or by combining several different projection patterns in the same image, making it possible to capture only one frame [14,15].

In our work we use the fact that the expected shape of the object is known, i.e. that there exists a design model describing the object. By using information from this design model, the shape of the object which should not deviate much from the expected shape, can be obtained with only one fringe pattern recording. Hence, measurements will be insensitive to vibrations and other disturbances due to movement in the measurement location. As with all optical measurement methods it is essential that all parts of the surface are illuminated and that the light is scattered back to the

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cameras. Problems may appear if the object has high reflectivity since this could give specular reflections from the projected light or other light sources.

When the surface is measured and the object points are obtained we compare the result with the design model. For making that possible we have to find a rigid body transformation of the object points so that they fit the design model. This general problem is discussed in e.g. [16–19]. There are many applications for a matching like this. One of them, probably the most well documented one, is inspection of free-form surfaces. There exist a number of papers discussing the inspection problem, some of them are [1,20,21]. In order to do the transformation fast for repeated use we are using a data-structure presented in [22]. The design model is pre-processed once before the measurements.

Our method to measure the surface of an object by using its design model is described in Section 2. In Sections 3 and 4 a description of the design model representation and the method for finding the surface transformation are found. Finally an example of an application is given in Section 5.

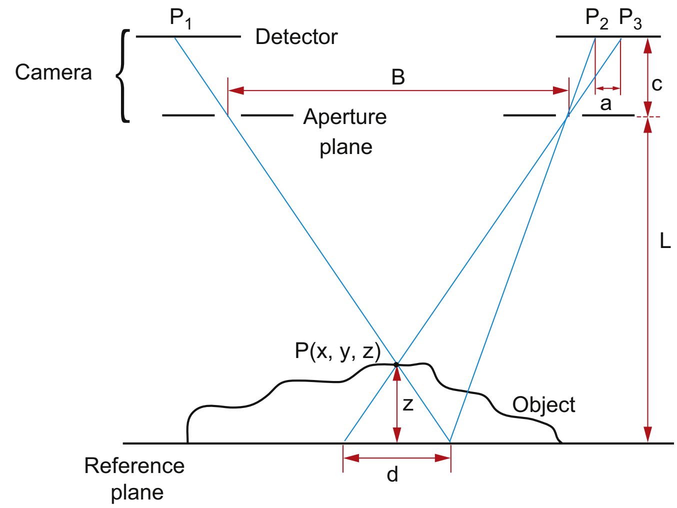

Fig. 1. Schematic sketch of the stereo camera system.

2. Shape measurement method

We use a stereoscopic camera system together with projected sinusoidal fringes to measure the shape of an object. Since the projected light becomes symmetric in the two cameras it is possible to distinguish it from asymmetric light such as e.g. specular reflections. Due to the continuity of the fringe pattern the accuracy in the measurements becomes higher than if a random pattern is used.

A rigorous examination of this method to optically measure the shape of an object is done by Rosendahl et al. [23]. Equations are derived which can be used in the shape determination. To get an overview of the approach used we give a brief description in this section.

In our application it is important that the measurement is fast in order to freeze mechanical disturbances and to be able to use it on-line. To speed up the measurements only one image recording is used. This is possible firstly because the expected shape of the object is known, i.e. we have the design model. And secondly because we use two cameras, i.e. an estimation of the unwrapping can be done using one camera and the correctness of it can be controlled using the other camera. In Sections 2.1 and 2.2 the different parts of the active stereo camera system used in this paper are described and in Section 2.3 the approach to achieve the shape from the measurements is explained.

2.1. Stereo camera system

A schematic sketch of the imaging part of the measurement system, the stereo camera system, can be seen in Fig. 1. It consists of two cameras that look at the object from different directions. The camera to the left is defined as the main camera, the camera whose pixels are used to define the coordinates of the object, and the camera to the right is the slave camera. The cameras are aligned in order for them to see the same scene when looking at the reference plane, hence detector points P_1 and P_2 have the same position on the two detectors and image the same point on the reference plane. However, when an object is positioned in the measurement volume P_3 and P_1 become corresponding points. This means that there is a displacement a between the positions on the two detectors that depends on the object height. The distances L, B and c that can be seen in Fig. 1 are determined by calibration of the system.

To be able to calculate the shape of the object it is important that the information from the two cameras that are used in the calculation represents the same part of the object. To localize different parts of the object there has to be features on the object that can be seen by both cameras. If there are not, such features have to be added to the object in some way. One way to do this is to project a pattern on the object, i.e. to make the system active, and that is the method we have chosen.

2.2. Projected fringes

In this work the projected pattern is fringes and due to the different viewing angle of the cameras the intensity images will look a little different in the two cameras. Figs. 2(a) and (b) are real images captured with the slave camera and the main camera, respectively. The fringes are sinusoidal and can be described by

$$\begin{aligned} I(x,y) &= a(x,y)+b(x,y)\cos[\phi(x,y)+2\pi f_0 x] \\ &= a(x,y)+c(x,y)e^{i2\pi f_0 x}+c^*(x,y)e^{-i2\pi f_0 x}, \end{aligned} \tag{1}$$

where $a(x,y)$ is the background intensity, $b(x,y)$ is the modulation of the fringe pattern, $\phi(x,y)$ is the phase in the fringe pattern, f_0 is the spatial carrier frequency, $c(x,y)=b(x,y)\exp(i\phi(x,y))/2$, and $*$ denotes the complex conjugate. The phase, $\phi(x,y)$, is the parameter that is used as the feature that can be recognized in both cameras. In Fig. 2(c) the frequency spectrum of the image from the slave camera is shown. The bright spots positioned at the carrier frequencies, f_0 and $-f_0$, in Fig. 2(c) represents the $c(x,y)$-terms in Eq. (1) and the spot at $f_x=0$ represents the $a(x,y)$-term.

2.2.1. Phase extraction

To be able to use the information in the projected fringe pattern the phase distribution, $\phi(x,y)$, is calculated from the intensity image. There are mainly two ways of doing this. The first way is to use phase-stepping in which several images are captured and the phase of the fringe pattern has a constant offset between each image [24]. The phase can then be calculated using a phase-stepping algorithm. The downside with this method is the time it takes to capture all the images needed. Due to this a faster way to achieve the phase distribution, the Fourier-transform method [25], is chosen. With this method the phase is extracted by transforming the intensity image to the spatial frequency spectrum, see Fig. 2(c), and then determining $c(x,y)$ by applying a spatial filter on one of the carrier frequency components. The wrapped phase in each camera can then be calculated according to

$$\phi(x,y) = \tan^{-1}\left(\frac{\mathrm{Im}\{c(x,y)\}}{\mathrm{Re}\{c(x,y)\}}\right). \tag{2}$$