ON THE CALIBRATION OF MAPVISION 4D SYSTEM

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ABSTRACT:

Mapvision 4D measurement machine uses video cameras and a light projector to quickly make a precise 3-D point cloud from a given small-scale 3-D object. The use of more than just two cameras makes it possible to control the quality of the measured data, which makes Mapvision 4D more flexible than conventional 3-D measurement machines. The calibration of this kind of photogrammetric machine requires that all possible effects due to the optical, electronic, and mathematical transformations from the 3-D space to the video images have to be taken into account. The calibration is made using a free-network bundle adjustment, which is constrained using known distances and points on precise planes. With the first prototype, an operational measurement accuracy of ± 5 µm is achieved.

1. INTRODUCTION

Mapvision 4D is a new optical 3-D coordinate measurement machine for on-line reverse engineering and quality control applications, e.g., in industrial production of small objects. It uses photogrammetry to measure a 3-D point from the images of the point. In the first prototype of the machine, the effective measurement volume is about 200 mm × 200 mm × 100 mm, and the object accuracy is about ± 5 µm. The measurement speed is currently about 80 points per second. The measurement system contains a standard PC with one or more digitising cards, four or more CCD video cameras (current resolution 768×576), a light scanner capable to project multiple light points on the measured object surface, and a rotating table allowing full registration around the object. The use of more than just two cameras makes it possible to control the quality of the measured data. The object is measured in a dark cabinet. The controlling computer and necessary power supplies are in a separate enclosure (Figure 1).

Figure 1. Mapvision 4D.

2. MEASUREMENT PRINCIPLE

The measurement using Mapvision 4D is based on principles of photogrammetry. First, the system is carefully self-calibrated, by determining the perspective transformations from the object space to the digitised video images using collinearity condition, simultaneously adjusting the unknown interior orientations and additional parameters for lens distortions. Once calibrated, it is possible to quickly compute the 3-D coordinates of any object point that can be seen in the cameras by using intersection. The final result is a dense 3-D point cloud representing the measured object surface. The calibration needs not to be repeated until it is accidentally broken or needs to be updated. The effect of thermal expansion and mechanical strain are also minimized using carbon fiber composite material in the mechanical construction of the machine.

In the on-line measurement mode, a specially designed light scanner, or projector, is used to project one or more light spots on the surface of the measured object. Currently, up to 16 spots in a 4×4 grid can be used (Figure 2).

The measurements space is darkened, so the light spots appear white in otherwise dark images, and their grey-scale weighted centroids are easily measured automatically. The intensity of the light can be adjusted so that the determination of the sub-pixel position is optimal. The smaller spot size, the smaller details can be measured. For accuracy reasons, however, the shape of the spot should be as circular as possible, and the size should be large enough to give sufficient information for the sub-pixel position determination. The smallest allowable spot size seems to be about 3×3 pixels, limiting the smallest detail size to about 0.8 mm. To reach smaller details in the 3-D object space means that the resolution of the cameras should be increased, or the cameras should be placed closer to the measured object.

A heuristic algorithm, based on epipolar geometry, is used to find the corresponding observations among the points seen in different images. For example, using a 16-point grid, 7-16 points usually get correct corresponding observations from at least three images. Points having observations in only two cameras are ignored as unreliable. In planar or smooth object surface patches, the correct combinations of all points are usually found. The 3-D coordinates can then be reliably computed using intersection. For each 3-D point, a quality index is also obtained which indicates how well the corresponding projection rays intersected in space. This can be used to filter the data before any further processing in a suitable 3-D modelling program.

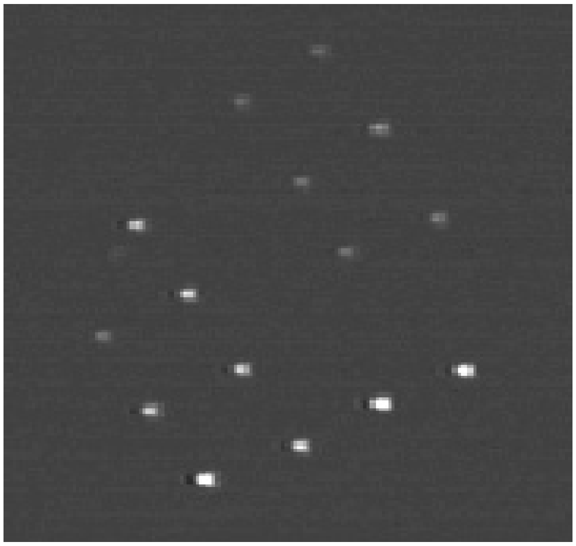

Figure 2. 16 light spots projected on an object.

The measured area can be programmed in advance using the movable light projector and the rotating measurement table. The number of measured points and the desired density of points can be freely chosen. Actual measurements from different rotation table positions are transformed to the same base coordinate system automatically by using special target points placed in the table.

For different materials, a different light source can be chosen. For most metals, plastics and soft materials, white light is suitable. For translucent plastics and glass, laser light is preferred.

3. CALIBRATION

The Mapvision 4D system requires careful system calibration to get it to measure in a correctly scaled, orthogonal 3-D coordinate system. The calibration is performed using a standard free-network bundle adjustment, which determines the relative positions and orientations of the cameras, as well as the unknown interior orientations and various additional lens distortion parameters of each camera. The absolute scale of the coordinate system is fixed by observing the end-points of a known scale bar, and by using the distance as a constraint in the adjustment. The distance should be observed in sufficiently many (say, 50-100) different orientations and positions, well distributed in the whole measuring volume, in order to get the best calibration results. It is better to use arbitrary rather than regular orientations and positions for the calibration distances. The observations are averaged over several repeated measurements, which improve the quality of the observations and makes the calibration more robust. The original calibration method is described in article (Haggrén and Heikkilä, 1989).

Approximate values for the calibration can be obtained by using at least six known 3-D points and the well-known DLT-method, or the all-from-scratch method described in (Niini, 2000), or simply by using the values from a previous calibration. The last method is especially suitable when recovering an accidentally broken calibration. Either a complete recalibration, or a quick determination of only the external orientations is possible.

When planar circular targets are used, the centre of the original circle is not projected on the actually measured centre of the image of the circle. This image is usually an ellipse, except when the image plane and the plane containing the original circle are parallel and the image is also a circle (Heikkilä, 1997). Using a triangle-shaped, three-target calibration tool, this effect can be taken into account (Figure 3).

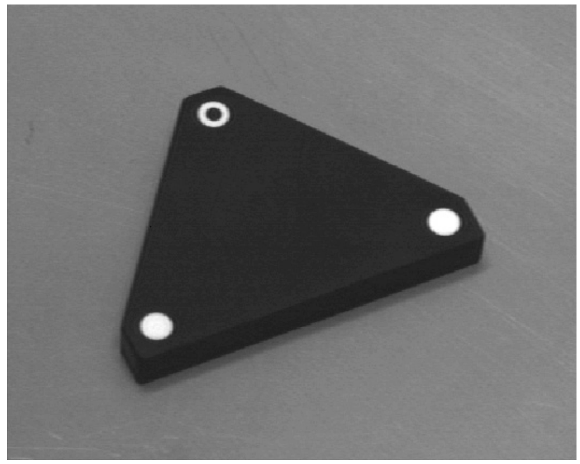

Figure 3. Calibration tool.

The third, ring target is used to recognize and order the targets correctly, and the three points together determine the orientation of the triangle with respect to the image planes, so that a projective correction to the image observations can be made iteratively during the adjustment. The projective corrections could also be avoided by using spherical targets.

It is possible that using an insufficient number of distances in the calibration may leave the final 3-D coordinate system locally slightly curved. This probably comes from the combined effect of the higher order radial distortion coefficients and the sparsity of the observed distances. There may exist quadratic saddle surfaces where the observed distances are correct, but the coordinate system is not homogeneously straight.

The orthogonality of the 3-D coordinate system can be further strengthened by measuring points (using the light scanner) along a known plane whose flatness is a magnitude better than the desired accuracy of the system. The plane can be observed in several different positions and orientations to remove any possible local curvature of the coordinate system. The image observations of these points enter the adjustment, and the corresponding 3-D points are constrained to lie on the same plane. Each different plane orientation adds four new parameters in the adjustment. The equation $AX+BY+CZ+D=0$ can be used, which simply states that the 3-D point with coordinates X, Y, Z lies on the plane determined by parameters A, B, C, and D. Because only three of these parameters are independent, a normalizing constraint equation is also needed: $A^2+B^2+C^2+D^2=1$.

In Mapvision 4D calibration, a steel plate, sized 200 mm × 200 mm × 20 mm, whose flatness is better than 2 µm, has been tested. In practice, the plane is observed in 5-7 different positions, always observing about 100 regularly distributed points from the surface of the plane. This makes the equation system of the calibration larger, but also guarantees a homogeneously straight coordinate system.

When calibration measurements and actual operational on-line measurements are made using different methods under different lighting conditions, the 3-D scales of the respective measurement systems tend to be slightly different. Therefore, it is also reasonable to only fix the calibration distance to the nominal value, and adjust the final scale of the 3-D coordinate system only afterwards in an absolute orientation using a known 3-D object. The exact dimensions of the object have to be determined separately, e.g., using a high precision coordinate measurement machine. The corresponding dimensions have to be extracted from the measured point cloud too, using a suitable 3-D modelling program, in order to get the scale difference correctly adjusted.

4. CONCLUSIONS

This article presents the main principles of the calibration method used with a new optical Mapvision 4D measurement machine. The calibration is based on precise analytical photogrammetry, and it takes into account all reasonable effects that can occur during image formation from the object to the digitized video image. The calibration is made using free-network bundle adjustment, which is constrained using known distances and points on precise planes. Hence, the 3-D measurement accuracy of Mapvision 4D system comes solely from its sophisticated calibration method, rather than from any high precision machinery.

References

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