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Performance Characterization in Automated Optical Inspection using CAD Models and Graphical Simulations

Abstract: The important role of automated optical inspection in the manufacturing process necessitates the design of optimized and precise inspection setups which can fulfill the application demands. Due to the high dimensionality of the design space, a manual choice of the geometrical and optical parameters is tedious and often not optimal. In this paper, we propose the calculation of two comprehensive evaluation metrics, namely the lateral resolution and the measurement uncertainty, based on using a CAD model of the workpiece and real-time graphical simulations. Automatic setup evaluation enables us to determine the setup adequacy with respect to the part tolerances and inspection quality requirements, which opens up the path to automatic optimization and virtual rapid prototyping of machine vision systems. We present the optical inspection of a cylinder head using laser triangulation as an application. Based on graphical simulation results, the proposed metrics are evaluated for different configurations of the setups and the achieved performance characteristics are compared against the part inspection tolerances on different areas of the CAD model.

Keywords: Automated optical inspection, performance characterization, real-time graphical simulations, lateral resolution, measurement uncertainty, CAD-based inspection planning, prototyping

1. Introduction

Finding the optimal design of a machine vision setup is a time-consuming process, requiring a lot of engineering experience [1]. To verify if a product has been manufactured within predefined tolerances, the inspection setup must be accurate and precise enough to be applicable to the task. A manual system design based on physical samples usually leads to a trial and error process. Moreover, the design space of optical inspection setups is often very large, including - besides other parameters - the positions and orientations of the camera(s) and the illumination source(s) as well as optical properties of the participating devices. Therefore, a setup design in this high-dimensional space is tedious and can end up in a non-optimal compromise between requirements. In this paper, we introduce and calculate performance evaluation metrics for the evaluation of optical inspection setups based on using CAD models and graphical simulations. The simulations enable us to efficiently evaluate different setup configurations without the need to realize the setup physically. Therefore, this opens up the path to automatic setup optimization and fast prototyping of machine vision systems. We have focused on the optical inspection of a cylinder head, as an example of a geometrically complicated workpiece, using laser triangulation [2] which is an affordable and widely used inspection technique. We further evaluate the inspection setup in terms of two important performance characteristics, the “lateral resolution” and the “measurement uncertainty” which together assess the adequacy of the setup. Furthermore, we compare the achieved performance metrics with the expert-defined tolerances on the CAD model.

In the literature of sensor planning, authors mainly seek to automate the process of view-point selection [3] by optimizing the setup design according to some defined evaluation criteria. Therefore, appropriate definition and calculation of the performance criteria is of central importance to sensor planning. Since the interaction of the light in the scene is at the heart of an optical inspection system, the evaluation of most performance characteristics is realized through ray-tracing. Scott [4] analyzes the measurability for coarsely sampled points on the surface and indicates the sensor visibility analysis as computationally expensive. Other authors [5] have set geometrical constraints to indicate the visibility of a mesh face. However, geometrically complex triangulated meshes often consist of numerous triangles which are non-uniform in area, can be partly visible, or vary in resolution. Moreover, the majority of the works only aim at optimizing the surface coverage [6]. A few authors have also included optical constraints such as resolution, focus, and field of view [7], while recent works have also taken the uncertainty of the measurement into account [4]. The uncertainty models are typically empirical and device dependent and only take a few parameters (e.g. distance, sensor viewing angle) into account. Cajal et al. [8] follow a similar intention to simulate a laser triangulation setup where they also account for some sources of uncertainty and propagate them using a Monte-Carlo numerical sampling. Such a method for uncertainty propagation is not suitable for the current application since the sampling procedure needs to be repeated for each 3D measured point and in each setup configuration [9]. In this paper, we apply an analytical second-order uncertainty propagation which is computationally very efficient.

This paper is organized as follows: upon reviewing the laser triangulation methodology in the next section, we introduce the two performance criteria for the setup evaluation in section 3. Section 4 briefly discusses the real-time graphical simulation library implemented for the simulation of the measurement. Section 5 demonstrates the evaluation results for the inspection of a cylinder head in a laser triangulation setup.

2. Laser Triangulation Measurement

In a laser triangulation inspection, the workpiece is moved along a scan direction while illuminated by a laser line. In the captured image, the peak intensities at the lateral center of the illuminated profile are extracted and processed to yield a set of surface coordinates in 3D space. The finite resolution of the sensor results in a finite set of measured points in each frame, which together form a point cloud of the workpiece. The 3D measurement is achieved by solving a system of linear equations, in which two of the constraints are determined by the 2D camera projection and the third constraint is provided by the laser plane equation. A detailed mathematical derivation of the 3D measurement is discussed in our previous work [9] .

Figure 1 illustrates the schematic of the setup and the main geometrical degrees of freedom that we have considered for the simulation and setup evaluation. Each valid choice of the set of parameters is called a geometrical constellation. A geometrical constellation together with a specific set of optical parameters (e.g. focal length, sensor size, etc.) is referred to as a setup configuration.

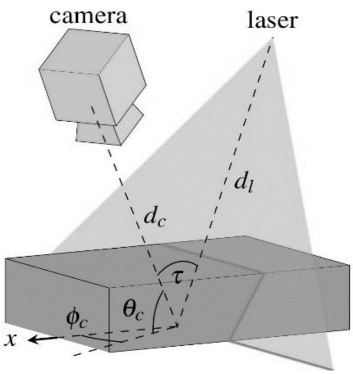

Figure 1: Laser scanning system and the geometrical degrees of freedom. The object is moved along the x-axis. θ_c and ϕ_c define the camera orientation. The camera and laser distances are denoted by d_c and d_l, respectively. The τ angle is called the triangulation angle.

3. Performance Characterization

In this section, we propose the calculation of two comprehensive performance metrics, namely the "lateral resolution" and the "measurement uncertainty" based on real-time graphical simulations. As we later discuss in Section 4, by efficiently simulating the measurement process, we compute the simulated 3D measurement point cloud for each desired constellation and further calculate the two metrics to evaluate the simulated setup in terms of resolution and precision, respectively.

The **lateral resolution** metric is defined as the minimum distance between two distinguishable measurement points [10]. Therefore, it can be approximated by the local density of the resulting point cloud. This metric is an extended version of the commonly used Boolean visibility [4], since a local point density of zero indicates a local invisibility. To estimate the lateral resolution, we first uniformly sample the triangulated surface of the initial CAD model with a high resolution. The uniform sampling is achieved by selecting a triangle with a probability proportional to its area, then sampling a point on its surface uniformly. This only needs to be performed once and we use the same set of sampled points for the all setup evaluations. Based on the simulation results, we search for the simulated measurement points located in the neighborhood of each sampled point, using a kd-tree data structure to accelerate the search. This way we are able to estimate the local average distance between the points at different parts of the CAD model. However, the resolution alone cannot characterize a setup unless we take the respective uncertainty into account. Therefore, this metric is complemented with measurement uncertainty to achieve a comprehensive setup evaluation criterion.

The **measurement uncertainty** metric indicates the dispersion of the measurement value around the nominal value due to the limited precision of the measurement. The estimation of the measurement uncertainty is primarily based on applying our previous work [9] on the simulated point cloud, where we have proposed an uncertainty propagation framework to model different sources of uncertainty in the measurement process with appropriate random variables, estimate the standard deviation of the random variables in the setup, and propose a probabilistic method to propagate them through the measurement. The uncertainties that are modeled belong to three different groups: laser detection uncertainties on the image, geometrical positioning uncertainties of the camera and the laser, and the camera optical calibration uncertainties. The modeled uncertainties are then propagated using a second-order approximation method which results in a 3×3 covariance matrix for each 3D measured point, describing the dispersion of the resulting point in 3D space. This covariance matrix describes a correlated 3D uncertainty for each point and can be used to calculate the measurement standard deviation along each direction of interest. To apply a worst case analysis, we evaluate the uncertainties along the direction with the highest uncertainty (standard deviation). This is possible by applying an eigenvalue decomposition on the corresponding estimated 3D covariance matrix.

4. Graphical Simulation

To evaluate a specific setup configuration, we simulate the measurement to obtain the 3D point cloud measured in the desired configuration. To this end, we have implemented the Rasterization Simulation Library (RSL) which simulates the image acquisition process for a specific geometrical and optical configuration (see Figure 2). The simulation input currently includes the geometrical constellation (as in Figure 1), the laser properties, such as wavelength, focal distance, divergence and opening angle, the camera resolution, and above all, the CAD model of the workpiece. The graphical simulations are based on rasterization techniques [11], which can be performed very quickly even on commodity hardware, making them an ideal fit for our needs. Using the OpenGL library, we first check for all surface points projected onto a camera pixel whether they are illuminated by the laser line and visible to the camera. We use a shadow map check, followed by a calculation of the laser beam width at the surface to determine the illumination. The visibility to the camera is resolved by the depth buffer. Surface points fulfilling both criteria are then evaluated with regard to whether the analytical intersection between the laser plane and the surface occurs in the frustum of the affected camera pixel. Surface points whose pixel boundaries contain the analytical intersection then constitute the final set of points for a frame. Having determined a set of points for each frame, we combine them to form a point cloud of the model. This point cloud is then used for the calculation of the two aforementioned performance metrics.

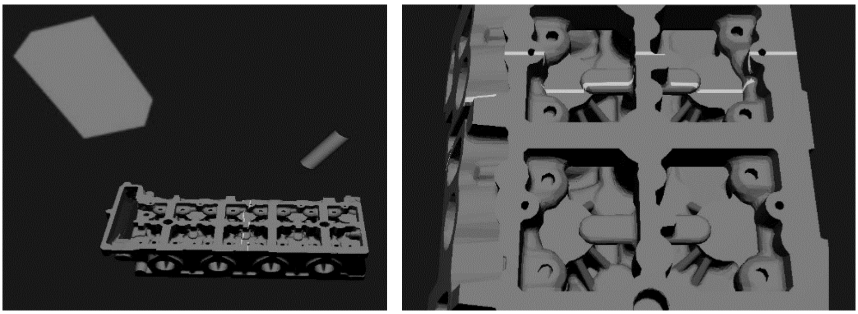

Figure 2: RSL simulation. **Left**: Free view. The box and the cylinder represent the camera and the laser, respectively. **Right:** The same scene from the camera's view.

5. Evaluation of a Cylinder Head Inspection

In this section, we simulate a cylinder head inspection process in a laser triangulation setup and evaluate the proposed performance criteria on the simulation results. To compare the achieved performance characteristics with the expert-defined constraints at each specific part of the CAD model, the RSL simulation library supports segmented CAD models in which different parts of the model are associated with different resolution and uncertainty constraints. Figure 3 illustrates the segmented cylinder head CAD model which we have used in the simulations.

Figure 4 displays a demonstration of the results for the simulated cylinder head inspection. This result has been generated for the constellation in which $\theta_c = 60°$, $\phi_c = 0^{\circ}$, $d_c = 0.5\, m$, $d_l = 0.5\, m$ and $\tau = 30^{\circ}$, based on the setup geometry in Figure 1 and a camera image with 512×512 pixels. The wavelength of the simulated laser line is $530nm$ and has a focal distance of $0.3m$ and an opening angle of 90°. The triangulated cylinder head mesh model was moved at a speed of $2mm$ per frame during the measurement simulations, and the whole workpiece is scanned through 400 frames. The runtime for the simulation part is $0.39\, s$. This time was measured on a machine with an NVidia GTX780 graphics card and a Core i7 2600 CPU running at 3.4 GHz. The simulation efficiency enables us to simulate the measurement for many constellations and provides the possibility for the further optimization of the setup. The result of the simulation has been evaluated in terms of the lateral resolution and the measurement uncertainty. The runtime for calculating the performance metrics is measured to be $0.98\, s$ on the same machine.

For modeling the sources of uncertainty, we have considered a $0.2\, px$ standard deviation for the laser peak detection on the image, a $0.5\, mm$ standard deviation for the positioning of the laser and the camera which is a typical value for the repeatability of industrial robots (neglecting rotational uncertainties), $1\, px$ standard deviation for the focal length (pixel unit based on the ratio of the sensor size and pixel numbers), and a $0.5\, px$ standard deviation in estimating the projection center of the camera based on a

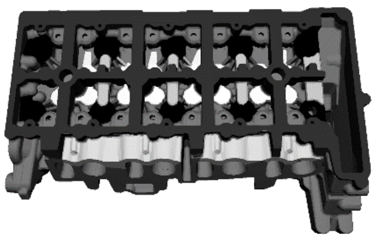

Figure 3: Segmented CAD model of the cylinder head. Different grayscales correspond to different CAD segments associated with different inspection requirements.

pinhole camera model [12]. The uncertainties are then analytically propagated based on a second order approximation, as described in [9], and each point is associated with a 3×3 covariance matrix which corresponds to an ellipsoid in the 3D space. We have further analyzed the ellipsoids and computed the variance along the direction with the largest spread, which indicates the direction with the largest uncertainty. This variance corresponds to the largest eigenvalue of each estimated covariance matrix. Finally, both estimated metrics are compared against the expert-defined constraints, separately for each CAD segment. Figure 4 illustrates the achieved performance metrics in this constellation and Figure 5 displays the pass or fail condition of the metrics on different areas of the model according to the given tolerances.

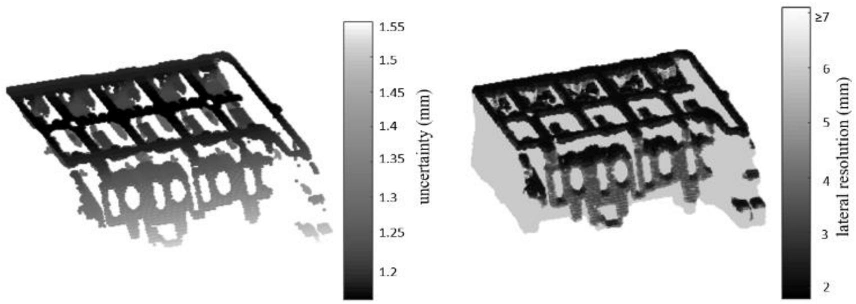

Figure 4: Performance characterization of cylinder head inspection in a laser triangulation setup. **Left:** The estimated measurement uncertainty along the direction with the largest standard deviation. **Right:** Achieved lateral resolution. The brightest area corresponds to unmeasured parts.

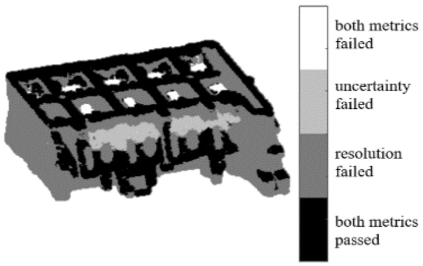

Figure 5: The final inspection evaluation based on the expert-defined tolerances.

6. Conclusion

The described performance characterization method can be applied to efficiently evaluate a laser triangulation setup for each desired geometrical constellation and optical parameters. Therefore, one is able to use this evaluation framework for automatic or semi-automatic setup optimization with the goal to best fulfill the inspection requirements. The efficiency of the method, which is mostly achieved by the hardware accelerated simulations can turn this approach into a suitable solution for setup optimization and rapid prototyping of optical inspection setups with geometrically complex CAD models and specific inspection requirements.

7. Acknowledgment

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