Multi-View Planning for Simultaneous Coverage and Accuracy Optimisation

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Multi-View Planning (MVP) for high fidelity three-dimensional (3D) reconstruction and inspection solves the problem of finding an efficient sequence of views allowing complete and high quality reconstruction of complex objects. Given a CAD model – or coarse 3D scan, or time of flight (TOF) 3D scan – of the object, our objective is to jointly evaluate accuracy requirements and coverage during planning, to optimise the reconstruction procedure.

In model-based view planning, one fundamental approach is the evaluation of a visibility matrix [4, 5]. This matrix encodes the visibility of discrete surface elements (surface space) from view candidates (view point space). Tarbox' and Gottschlich's [5] approach was limited to viewpoint candidate creation on a view sphere around the object. Scott [4] further developed this method by creating arbitrary generalised viewpoints in an optimal scanning zone. The extension of the statistical E-criterion to next best view (NBV) planning was recently introduced by Trummer et al. [6] for online path planning for a 3D reconstruction approach without active illumination.

In this paper we present a novel model-based MVP approach, which models measurement uncertainty additionally to coverage. Our paper's contribution is the accuracy optimising MVP approach using the extended E-criterion, *simultaneously* taking uncertainty and coverage into account. In the paper we finally evaluate different planning methods using the benchmark object and scheme from [2].

For complex objects, analysis of the viewpoint candidate creation scheme [4] revealed limitations for surfaces in concavities, as well as in the presence of configuration space constraints. We therefore formulated an adaptive viewpoint generation scheme, taking substitute view candidates on a loxodrome (or rhumb line, see [1]) around the optimal, yet unfeasible candidate, into account.

To optimise accuracy as well, we extended the statistical E-criterion [3, 6] to model based view planning using active illumination. To predict the measurement uncertainty, we a priori calibrated a model of the sensor's measurement characteristic covariance matrix Σ_c. Using eigen decomposition of Σ_c, we obtain eigenvalues $\lambda_c^{(1)} \geq \lambda_c^{(2)} \geq \lambda_c^{(3)}$ and corresponding perpendicular eigenvectors $\xi_c^{(1)}, \xi_c^{(2)}$ and $\xi_c^{(3)}$. Applying alignment of $\xi_c^{(1)}$ along a candidates viewing direction and scaling $\lambda_c^{(1)}$ according to the determining uncertainty influences, we yield the covariance matrix Σ_i for scanning a surface from viewpoint v_i. The uncertainty from surfaces seen from multiple views can now be estimated by

$$SE_{\overline{\Sigma}_n} = \frac{\sigma_n}{\sqrt{n}} \equiv \frac{\sqrt{\lambda_n^{(1)}}}{\sqrt{n}}\,, \tag{1}$$

with $\lambda_n^{(1)}$ the largest eigenvalue of the cumulative covariance matrix $\overline{\Sigma}_n$ after n views:

$$\overline{\Sigma}_n = \frac{1}{n}\sum_{i=1}^{n} \Sigma_i\,. \tag{2}$$

λ_c is scaled by $f_{ia}\left(\mathbf{n}, v_i\right)$ (incidence angle), focal depth $f_{fd}\left(d_{fd}\right)$ and sampling density $f_{sd}\left(d_{s,v_i}\right)$ as follows:

$$\lambda_i = \frac{f_{sd}\left(d_{s,v_i}\right)}{f_{ia}\left(\mathbf{n}, v_i\right) \cdot f_{fd}\left(d_{fd}\right)}\lambda_c\,. \tag{3}$$

Finally we calculate the optimal viewing direction $\mathbf{o}$ depending on $w_{ne} = \sqrt{\lambda_n^{(2)}/\lambda_n^{(1)}}$, the weight with regard to $\overline{\Sigma}_n$ error ellipsoid's eccentricity and the respective triangle's surface normal $\mathbf{n}$:

$$\mathbf{o}_E = \frac{\mathbf{o}_E^{'}}{\left|\mathbf{o}_E^{'}\right|}\,,\ \text{with}\ \mathbf{o}_E^{'} = \mathbf{n} - \frac{\mathbf{n}^{\mathrm{T}}\mathbf{v}_1}{\mathbf{v}_1^{\mathrm{T}}\mathbf{v}_1}\mathbf{v}_1\,, \tag{4}$$

$$\mathbf{o} \quad = \quad -\left(w_{ne}\mathbf{n} + \left(1 - w_{ne}\right)\mathbf{o}_E\right)\,. \tag{5}$$

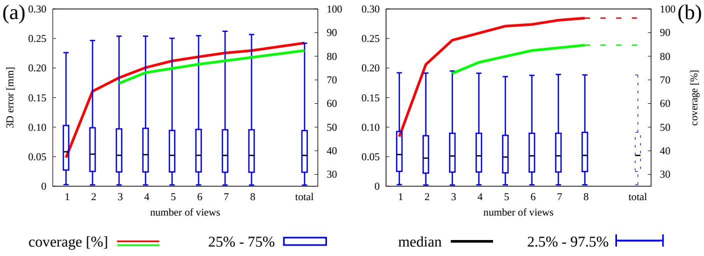

Figure 1: Comparison of predicted (red) and realised (green) coverage, and accuracy for the whole NBV test object: (a) baseline approach [4]; (b) E-criterion with $[\kappa = 4.0; \tau = 1.7; SE_t = 0.08]$.

To examine our approach to view planning, we compared different planning strategies using the NBV benchmark from Munkelt et al. [2]. It evaluates the planner's performance in reconstructing a complex measurement object. We analysed *view count*, *coverage* (the percentage of scanned compared to the scannable object surface) and *reconstruction error*. Figure 1 shows the planner's coverage and error estimation, as well as the actually achieved coverage after the specified number of scans. Our E-criterion based planning approach achieves better overall coverage at similar error rates then Scott's baseline approach [4].

Our conclusion is that the proposed MVP approach for *simultaneously* optimising reconstruction completeness and accuracy is effective for high fidelity scanning of complex objects, yielding higher coverage while maintaining similar error levels than comparable planning methods.

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