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Surfel-Based Next Best View Planning

Riccardo Monica  and Jacopo Aleotti 

Abstract—Next best view (NBV) planning is a central task for automated three-dimensional (3-D) reconstruction in robotics. The most expensive phase of NBV computation is the view simulation step, where the information gain of a large number of candidate sensor poses are estimated. Usually, information gain is related to the visibility of unknown space from the simulated viewpoint. A well-established technique is to adopt a volumetric representation of the environment and to compute the NBV from ray casting by maximizing the number of unknown visible voxels. This letter explores a novel approach for NBV planning based on surfel representation of the environment. Surfels are oriented surface elements, such as circular disks, without explicit connectivity. A new kind of surfel is introduced to represent the frontier between empty and unknown space. Surfels are extracted during 3-D reconstruction, with minimal overhead, from a KinectFusion volumetric representation. Surfel rendering is used to generate images from each simulated sensor pose. Experiments in a real robot setup are reported. The proposed approach achieves better performance than volumetric algorithms based on ray casting implemented on GPU, with comparable results in terms of reconstruction quality. Moreover, surfel-based NBV planning can be applied in larger environments as a volumetric representation is limited by GPU memory.

Index Terms—Autonomous agents, range sensing, motion and path planning, computer vision for other robotic applications.

I. INTRODUCTION

A NEXT Best View (NBV) algorithm computes the best viewpoint of a depth sensor, mounted on a robot, to improve the knowledge of the environment by maximizing the expected information gain. Typical NBV algorithms operate iteratively in two phases: viewpoint generation and viewpoint evaluation. In the first phase, the free configuration space of the robot is explored to retrieve a set of candidate sensor poses. In the second phase, a view is simulated from each candidate sensor pose, given the current model of the environment, and then the most promising viewpoint is selected. The goal of the simulation is to estimate the amount of unknown space visible from the view pose, which in turn predicts the information gain. The view simulation phase is usually the most computationally expensive operation, which may limit the number of poses that can be evaluated in a reasonable time.

Unlike most works that address the NBV problem by using a volumetric representation of the environment, in this work a

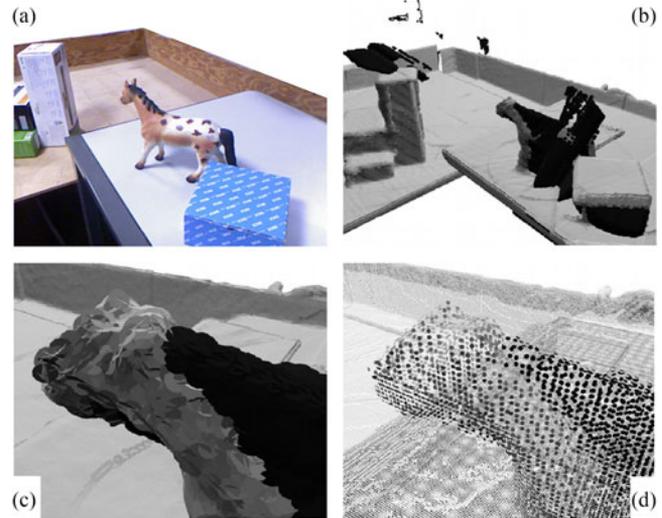


Fig. 1. (a) RGB image of the scene. (b) Incomplete surfel-based representation, with surface surfels (gray shading) and frontier surfels (frontels, black). (c) A closeup view. (d) Closeup view with surfel size reduced to 20%.

novel NBV evaluation strategy is proposed that exploits a surfel-based representation. A surfel is a surface element represented as a circular disk without explicit connectivity, described by geometric attributes such as position, radius, normal and color [1]. Multiple surfels may be assembled to describe a surface. Research interest on surfels has risen significantly as a set of surfels can be processed like a point cloud but it contains more information. A surfel cloud is also simpler than a polygon mesh data structure and it requires less memory than a volumetric representation. As an example, the ElasticFusion algorithm [2] has been proven capable of GPU-accelerated real-time 3D reconstruction on a surfel cloud.

In this letter, a novel kind of surfel is introduced, named *frontel*, in order to represent the frontier between empty and unknown space (Fig. 1). We exploit previous work [3] where the KinFu Large Scale algorithm, an open source implementation of KinectFusion [4] in the Point Cloud Library, was modified to reliably keep track of both empty and unknown voxels. Further changes have been made in this work to generate surfels and frontels in real-time during the KinFu reconstruction process, with minimal overhead. In the view simulation phase, frontels and surfels are rendered to simulate a depth image.

The proposed NBV approach was evaluated in a real setup including a robot arm with a Kinect sensor in eye-in-hand configuration. Results are compared with volumetric methods, where viewpoint evaluation was accelerated on GPU thanks to KinFu internal ray casting. The experimental evaluation shows a

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73 significant performance improvement for the surfel-based NBV
 74 algorithm, with a similar quality in 3D reconstruction. Most of
 75 the performance improvement is due to the opportunity to fit the
 76 whole 3D representation on GPU memory at once, which is not
 77 possible with a volumetric representation. Indeed, in volumetric
 78 NBV approaches, when observing different regions of space,
 79 parts of the environment must be loaded from CPU to GPU
 80 memory before viewpoint evaluation. Similarly, due to limited
 81 GPU memory, another advantage of surfel-based NBV planning
 82 against volumetric approaches is that it can be applied in larger
 83 environments. The paper is organized as follows. Related work
 84 is reported in Section II. In Section III, the proposed surfel-
 85 based NBV algorithm is described. Experiments and results are
 86 reported in Section IV. Finally, Section V concludes the work.

87 II. RELATED WORK

88 Next best view planning is a well established area of re-
 89 search in robotics [5]–[7]. Here we mainly review recent results,
 90 with the aim of showing that the use of volumetric approaches,
 91 requiring computationally intensive ray casting operations for
 92 viewpoint evaluation, remains prevalent. Most works focus on
 93 non model-based methods that do not assume an a priori model
 94 of the scene, while model based NBV planning requires both
 95 modeling and object recognition [8]. In [9] an approach was
 96 proposed which takes into account the position uncertainty of
 97 the sensor and that adopts a utility function that considers sev-
 98 eral factors like perception of unseen areas, navigation distance,
 99 reconstruction quality and fast occlusion estimation. Potthast
 100 *et al.* [10] presented a variant of the NBV problem that builds a
 101 belief model of the unobserved space for cluttered environments
 102 with occlusion. In [11] a frontier-oriented algorithm based on
 103 volumetric hierarchical ray tracing was introduced to speed up
 104 NBV evaluation.

105 In mobile robotics the view planning problem is constrained
 106 in the 2D plane [9], [12]–[18]. Senarathne *et al.* [12] presented
 107 a method based on surface frontiers, i.e. the boundary voxels
 108 of mapped surfaces adjacent to unmapped space. In [14] an
 109 adaptable and probabilistic object reconstruction approach was
 110 proposed to evaluate the information gain. An optimization was
 111 also introduced, based on a lookup table, for the evaluation of
 112 multiple view orientations from the same viewpoint. Isler *et al.*
 113 [15] exploited a probabilistic volumetric map and investigated
 114 an algorithm that estimates whether a ray is expected to hit the
 115 backside of already observed surfaces. Delmerico *et al.* [16]
 116 evaluated different information gain metrics for NBV planning
 117 using a probabilistic voxel map in terms of completeness and
 118 entropy. The comparative analysis indicated that the utility func-
 119 tion defined in [9] achieved the best performance, as well as a
 120 metric that gives higher weights to unobserved voxels close to
 121 already observed surfaces. Patten *et al.* [17] developed a model
 122 based system for outdoor active object classification using a mo-
 123 bile robot. Monte Carlo methods for planning new observations
 124 were adopted with time and distance constraints together with
 125 a non-parametric Bayesian regression classifier.

126 NBV planning has also been applied to aerial robotics. In [19]
 127 a receding horizon method was introduced based on sampling a

random tree of candidate viewpoints. The method scales better
 than a frontier-based planner in large environments. In [20] a
 2-stage planning solution was proposed that aims at achieving
 full coverage of the environment and global optimality of the
 exploration path.

Surface based approaches for NBV planning were investi-
 gated using triangular meshes [21]–[23]. Viewpoints were
 generated by examining the boundaries of the reconstructed
 surfaces. These methods do not model the surface between
 empty and unknown space, and, therefore cannot select the
 next best view by estimating information gain from unknown
 volume. Volumetric representations are also preferred for
 probabilistic approaches [15].

III. METHOD

141 The robot task is to perform a 3D reconstruction of the volume
 142 around a set of Points Of Interest (POIs), in a tabletop scenario,
 143 by taking a sequence of observations. It is assumed that the set
 144 of POIs is given as input to the system. For example, a POI
 145 may indicate the location of an object or a group of objects
 146 to be scanned. At the beginning of the task the robot has an
 147 initial, possibly incomplete, representation of the environment
 148 and the volume around each POI is cleared (set to unknown), as
 149 described in Section III-B. The NBV planning procedure is then
 150 executed. At each iteration candidate viewpoints are sampled
 151 on a view sphere with fixed radius around each POI, oriented
 152 towards the POI itself. In the view simulation phase, surfels and
 153 frontels are rendered to a virtual view (Section III-C). Then a
 154 score is computed from the rendered image (Section III-D). The
 155 score represents the expected information gain for the simulated
 156 sensor pose. The poses are attempted using a motion planner in
 157 decreasing order of scores. The first feasible solution is executed
 158 by the robot.
 159

160 In the proposed method surfels and frontels are generated
 161 on GPU in real-time during robot observations from the KinFu
 162 internal representation. Both surfels s and frontels f are circular
 163 disks in 3D space. Surfels separate empty from occupied
 164 space, while frontels separate empty from unknown space. In
 165 particular, surfel/frontel generation is performed during trun-
 166 cated signed distance function (TSDF) volume shifting opera-
 167 tions to optimize performance (Section III-A). The TSDF vol-
 168 ume is the volumetric representation of the environment used by
 169 the KinFu algorithm. As KinFu is able to keep in GPU memory
 170 only a limited volume, if the whole environment does not fit
 171 inside the TSDF volume KinFu Large Scale shifts the TSDF
 172 volume by unloading and loading parts of the TSDF volume
 173 from and to GPU memory according to sensor movements.

A. Real-Time Surfel and Frontel Generation

174 The TSDF volume is organized as a regular voxel grid. The
 175 TSDF assigns to each voxel the distance to the nearest sur-
 176 face, negative in occupied space and positive in empty space.
 177 The distance is truncated in the interval $[-v_{\max}, v_{\max}]$. Each
 178 voxel $c(x_c, y_c, z_c)$ holds a TSDF value v_c , i.e. the value of the
 179 TSDF at the center of the voxel, and a weight w_c which con-
 180 tains the number of times the voxel has been observed, up to a
 181

182 maximum. KinFu operates on a cubic TSDF volume with edge
 183 length $E = c_{\max}e$, where c_{\max} is the volume resolution and e is
 184 the voxel size. Whenever a point is observed by the sensor, the
 185 voxels on the ray between the observation and the sensor posi-
 186 tion are updated. However, only the volume inside the TSDF
 187 is updated by KinFu. The Large Scale extension of KinFu per-
 188 forms a shifting operation when the distance between the TSDF
 189 volume center and a virtual point, at about $E/2$ distance from the
 190 sensor along the z axis, is greater than $E/3$. A shifting operation
 191 translates the TSDF volume such that it represents a new region
 192 in space, centered at the the virtual point. Shifting ensures that
 193 the region currently observed by the sensor is the one represented
 194 on GPU and that it can be updated. Information contained in the
 195 intersection between the old TSDF volume and the new one is
 196 kept in GPU memory. Voxels with $w_c > 0$ and $v_c < v_{\max}$ outside
 197 the new volume are downloaded from GPU memory to RAM.
 198 Then, voxels are converted into points, described by position c
 199 and TSDF value v_c , and added to a TSDF point cloud. Points
 200 are reloaded to TSDF volume if a subsequent shifting operation
 201 moves the volume back in the old region. Due to memory con-
 202 straints, empty voxels with $v_c = v_{\max}$ are not downloaded by
 203 the aforementioned procedure. Therefore, in our previous work
 204 [3] an octree Ω was added to store w_c when $v_c = v_{\max}$.

205 Surfels s are circular disks in 3D space, with position p_s ,
 206 radius r_s and normal n_s . Color is not available in KinFu, but
 207 it is not required for the proposed NBV score computation.
 208 Similarly, frontels f have position p_f , radius r_f and normal n_f .
 209 The surface between the outside and the inside of objects is
 210 located in the TSDF volume between voxels having a different
 211 sign of v . That is, an empty voxel c is near the surface of an
 212 object if the following conditions hold:

$$\begin{cases} v_c \geq 0 \wedge w_c > 0, \\ \exists c' \in N_6(c) \mid v_{c'} < 0, w_{c'} > 0 \end{cases} \quad (1)$$

213 where $N_6(c)$ is the 6-neighborhood of voxel c . Similarly, the
 214 frontier between empty and unknown space is located where w
 215 changes from 0 to a positive value, i.e.

$$\begin{cases} v_c \geq 0 \wedge w_c > 0, \\ \exists c' \in N_6(c) \mid w_{c'} = 0 \end{cases} \quad (2)$$

216 Before a TSDF volume shifting operation occurs, surfels and
 217 frontels are generated from the old TSDF volume. A surfel
 218 centered on voxel c is generated, i.e. $p_s = c$, if condition (1)
 219 holds, whereas a frontel $p_f = c$ is generated if condition (2)
 220 holds. Generated surfels/frontels are added to two sets on CPU
 221 RAM, here named Σ and Φ respectively. To avoid duplication,
 222 existing elements of Σ and Φ inside the region represented by the
 223 old TSDF volume are cleared. These elements may have been
 224 generated by previous shifting operations in the same region.

225 The surfel local normal is estimated from the TSDF local
 226 gradient, according to the signed distance function properties,
 227 as follows (normalization omitted):

$$n_s(c) = \sum_{c' \in N_6} v_{c'} \frac{c' - c}{\|c' - c\|} \quad (3)$$

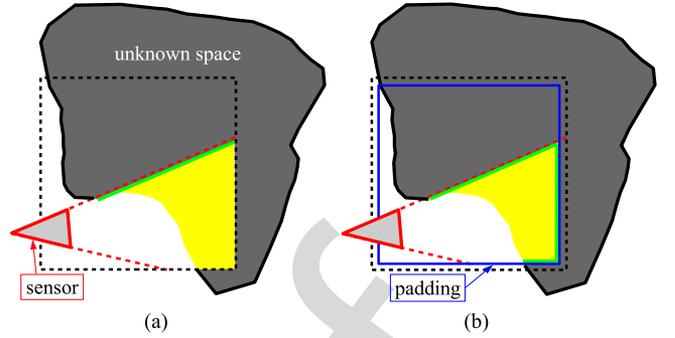


Fig. 2. The current position of the TSDF volume is marked with a black dashed square. The sensor observes towards the right, clearing the yellow unknown area. The green line indicates where frontels are generated (a) without and (b) with padding.

228 Conversely, a frontel normal is estimated from the 26-
 229 neighborhood N_{26} of the voxel c , as follows (normalization
 230 omitted):

$$K_w(c) = \begin{cases} 1 & \text{if } w_c > 0 \\ -1 & \text{if } w_c = 0 \end{cases} \quad (4)$$

$$n_f(c) = \sum_{c' \in N_{26}} K_w(c') \frac{c' - c}{\|c' - c\|} \quad (5)$$

231 The 26-neighborhood was chosen over the 6-neighborhood to
 232 reduce the quantization error. Indeed, unlike v_c , $K_w(c)$ as in
 233 (4) can assume only two values. Normal n_f is oriented from un-
 234 known space towards known space. Equations (1) and (2) place
 235 the surfel at the center of an empty voxel next to an occupied
 236 or unknown voxel. Therefore, occupied and unknown volumes
 237 are enlarged by $\delta_e = \frac{1}{2}e$ per side, i.e half the KinFu voxel edge
 238 e . To generate a surface without holes, the surfel/frontel radius
 239 must be set as half the distance between the two farthest vertices
 240 of a voxel, i.e. $\frac{\sqrt{3}}{2}(e + 2\delta_e)$. Therefore, the surfel/frontel radius
 241 may be approximated as $r_s = r_f = \sqrt{3}e$.

242 The surfel/frontel generation procedure [(1) and (2)] requires
 243 knowledge about the neighboring voxels. Voxels in contact with
 244 the TSDF volume surface are considered as a special case cov-
 245 ered by reducing the active TSDF volume by a one-voxel-wide
 246 padding. The padding is downloaded and uploaded from/to GPU
 247 as usual, but it is not updated with new data acquired by the sen-
 248 sor. An example of this issue is provided in Fig. 2. In case (a),
 249 without padding, the TSDF volume has been set to empty up
 250 to its right surface. Therefore, frontels are not generated in that
 251 area, leaving a hole in the surface enclosing unknown space. In
 252 case (b), the unknown values near the TSDF volume surface are
 253 not removed and frontels are correctly generated.

B. Initialization of the Regions of Interest for the NBV Task

254 Each POI defines a spherical region with origin p_{poi} and ra-
 255 dius R_{poi} . At the beginning of the task each spherical region
 256 around a POI is cleared and set to unknown. To this purpose
 257 the TSDF volume and the surfel/frontel-based representation
 258 must be managed in a consistent way. In the part of the sphere
 259

260 currently inside the TSDF volume, w_c is set to 0 whenever
 261 $\|c - p_{\text{poi}}\| \leq R_{\text{poi}}$.

262 Outside the TSDF volume, the update procedure is executed
 263 as follows. First, surfels and frontels inside the sphere are deleted
 264 from Σ and Φ . Then, frontels must be generated in Φ between
 265 the cleared volume and the empty voxels in octree Ω . Let $c \in \Omega$
 266 be a voxel outside the sphere, c has a known neighbor inside the
 267 sphere if the following conditions hold:

$$\begin{cases} \|c - p_{\text{poi}}\| > R_{\text{poi}} \quad \wedge \quad w_c > 0, \\ \exists c' \in N_6(c) \mid w_{c'} > 0, \|c' - p_{\text{poi}}\| \leq R_{\text{poi}} \end{cases} \quad (6)$$

268 Therefore, a new frontel is created at position $p_f = c$, with
 269 radius r_f and normal $n_f = (p_f - p_{\text{poi}})/\|p_f - p_{\text{poi}}\|$ when condi-
 270 tions in (6) hold. Finally, the voxels inside the sphere are set
 271 to unknown in Ω .

272 C. Surfel Rendering

273 The standard pinhole model is used for simulating the Kinect
 274 sensor. The depth image of a real sensor contains, for each pixel,
 275 the distance of the first intersection of a ray cast from the origin
 276 of the camera center passing through that pixel. Some pixels are
 277 left undefined, since the intersection may go below (or beyond)
 278 the minimum (or maximum) sensor range.

279 A sensor which follows the pinhole model can be simulated by
 280 rendering. For each surfel or frontel, position (3×32 -bit floats),
 281 normal (3×32 -bit floats) and radius (32-bit float) are provided
 282 to the rendering pipeline. In total, 28 bytes are required per surfel
 283 or frontel. In our approach, rendering generates an image that
 284 includes all information needed for NBV score computation.
 285 Unlike the real sensor, three possible results may occur for the
 286 virtual sensor pixels, i.e. a pixel is marked: a) occupied, if a
 287 surfel is rendered; b) unknown, if a frontel is rendered; c) out-
 288 of-range, if nothing is rendered or the surfel/frontel is out of the
 289 sensor range. A single real value o_{ij} is used for each pixel as the
 290 output of the rendering pipeline. Given the z_d depth in camera
 291 coordinates of the rendered surfel/frontel, the output value is set
 292 as:

$$o_{ij} = \begin{cases} z_d & \text{if (a)} \\ -z_d & \text{if (b)} \\ 0 & \text{if (c)} \end{cases} \quad (7)$$

293 Therefore, when rendered, surfels and frontels produce positive
 294 and negative depths respectively.

295 Image resolution, center point and focal length are known
 296 from the sensor intrinsic calibration. The maximum range of
 297 the sensor is used to set the frustum far plane, so that farther
 298 points are discarded. By setting background to 0, case (c) is auto-
 299 matically handled for points beyond maximum range. However,
 300 since surfels between the camera and minimum range occlude
 301 surfels behind them in the real sensor, they must be rendered
 302 with output value 0.

303 In the view evaluation phase TSDF volume shifting opera-
 304 tions must be simulated. The predicted TSDF volume is assumed
 305 centered on the POI which generated the view. Surfels/frontels
 306 outside the predicted position of the TSDF volume are rendered
 307 with $o_{ij} = 0$, as when the real sensor measures range data

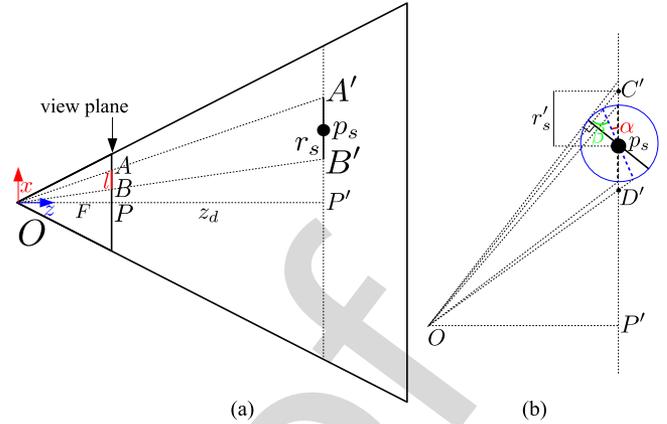


Fig. 3. (a) Surfel s , with position p_s and radius r_s , is projected to the view plane. Square size $l \geq \overline{AB}$ must be estimated. (b) A case in which l is underestimated. Distance OP is reduced to highlight the effect.

outside the TSDF volume such data do not contribute to the 3D
 reconstruction.

A point-based rendering technique is adopted to efficiently
 render surfels as points [24]. The default OpenGL pipeline ren-
 ders points as squares of size l facing the camera. A vertex
 shader is executed in parallel on GPU for each point sent to
 the rendering pipeline. In particular, each point is transformed
 into camera coordinates and the distance z_d is computed. The
 OpenGL pipeline is instructed to draw squares with size l by
 setting the variable `gl_PointSize` in the vertex shader. Each
 square may span multiple fragments, each corresponding to a
 pixel. For each fragment, a fragment shader is run by the
 OpenGL pipeline. The fragment shader computes the 3D distance
 of each fragment from the center of the surfel which gener-
 ated it. The fragment is discarded if the distance is greater
 than the radius r_s .

Estimation of a suitable square size l in the vertex shader
 is a non-trivial task. Indeed, the size must be large enough
 to encompass the entire surfel. However, setting a too large
 square size would cause generation of many useless fragments,
 thus deteriorating performance. If the surfel is roughly paral-
 lel to the image plane [Fig. 3(a)], l can be estimated as follows.
 Triangles $\triangle OAB$ and $\triangle OA'B'$, and also $\triangle OAP$ and $\triangle OA'P'$
 are similar, i.e.:

$$\frac{\overline{OP'}}{\overline{OP}} = \frac{\overline{OA'}}{\overline{OA}} = \frac{\overline{A'B'}}{\overline{AB}} \quad (8)$$

Therefore, given focal length F , edge l is estimated as:

$$l = \frac{2Fr_s}{z_d} \quad (9)$$

A similar estimate was performed in [24]. However, by using
 such formula, l may be underestimated as shown in Fig. 3(b),
 in a 2D example. This results in incompletely rendered surfels,
 cut by the bounding square. In the following, we provide an upper
 bound for this under-estimation.

Surfel s is rotated by angle α so that it appears slightly bigger,
 i.e. the projection of its top-most point onto the plane through
 p_s , parallel to the view plane, is in C' instead of A' . A similar

341 effect happens for the lower-most pixel, which now projects
 342 in D' . However, the error for D' is smaller, due to the minor
 343 distance from the sensor principal axis. The circle displayed
 344 around the surfel in Fig. 3(b) represents the possible positions
 345 of the top-most and lower-most points, by varying α values. The
 346 maximum distance $\overline{A'C'}$ occurs when the surfel is perpendicular
 347 to $C'O$, i.e. $\beta = \pi/2$. In this case, $\alpha = \angle P'OC'$. Therefore, the
 348 projected surfel radius $r'_s = \overline{p_s C'}$ is upper bounded as follows:

$$r'_s \leq \frac{r_s}{\cos(\angle P'OC')} \quad (10)$$

349 However, $\angle P'OC'$ can be at most equal to the sensor Half
 350 Field Of View (HFOV). Therefore, for a Kinect-like sensor,
 351 with $\text{HFOV} \approx 30^\circ$, $\cos(\text{HFOV}) = \sqrt{3}/2 \approx 0.866$. Hence, in
 352 the worst case a surfel is reduced by less than 14% its size.

353 D. NBV Score Computation

354 Standard NBV score computation methods assign a score
 355 equal to the number of unknown voxels visible from each pose.
 356 The more unknown voxels are visible, the higher is the infor-
 357 mation gain expected from that pose. In this letter we propose
 358 a novel score function where the total area of visible frontels
 359 is used to approximate the number of unknown voxels. Since
 360 frontels are generated to cover the area of the frontier between
 361 empty and unknown space, the total area of visible frontels is
 362 (approximately) proportional to the number of voxels in the
 363 frontier. The number γ_r of sensor view rays which intersect a
 364 frontier is computed from the rendering output (7) as:

$$U_o(o_{ij}) = \begin{cases} 1 & \text{if } o_{ij} < 0 \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

$$\gamma_r = \sum_{ij} U_o(o_{ij}) \quad (12)$$

365 However, each frontel f contributes to γ_r proportionally to
 366 its projected area A_f^p . Therefore, frontels close to the camera
 367 contribute excessively. This high contribution is not consistent
 368 with the standard score function that counts the number of un-
 369 known visible voxels. Indeed, in the standard score function a
 370 voxel close to the camera counts as 1, like any other voxel. In
 371 the following, a more appropriate score function is defined by
 372 introducing a weighting factor.

373 Equation (9) in Section III-C relates distance z_d and radius r_f
 374 of a frontel (roughly parallel to the view plane) to the diameter l
 375 of its projection on the view plane. Also, due to (7), $z_d = |o_{ij}|$.
 376 Hence, the projected frontel area in pixels can be estimated as:

$$A_f^p = \pi \left(\frac{l}{2}\right)^2 = \pi \left(\frac{1}{2} \frac{2Fr_f}{z_d}\right)^2 = \left(\frac{F}{|o_{ij}|}\right)^2 A_f^v \quad (13)$$

377 where $A_f^v = \pi r_f^2$ is the actual frontel area. The weighted NBV
 378 score function is then defined as:

$$\gamma = \sum_{ij} U_o(o_{ij}) \gamma_{ij} \quad (14)$$

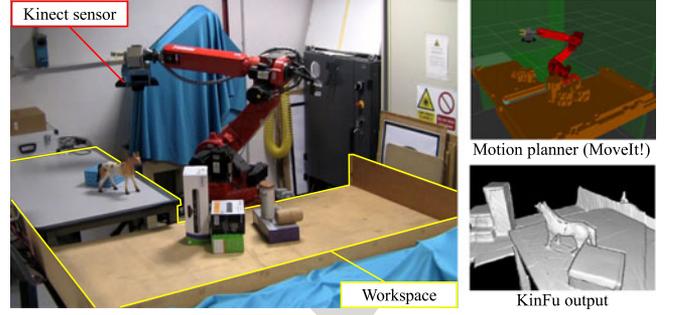


Fig. 4. The experimental setup.

where the weighting factor γ_{ij} is

$$\gamma_{ij} = \frac{A_f^v}{\max\{A_f^p, 1\}} \quad (15)$$

380 For frontels not too far away from the camera, (15) can be
 381 simplified by using (13) so that:

$$\gamma_{ij} = \frac{A_f^v}{A_f^p} = \left(\frac{|o_{ij}|}{F}\right)^2 \quad \text{if } A_f^p \geq 1 \quad (16)$$

382 i.e. γ_{ij} is set as inversely proportional to the projected surfel
 383 area A_f^p . Conversely, for distant frontels where the projection
 384 area A_f^p is smaller than a pixel, gain γ_{ij} becomes

$$\gamma_{ij} = A_f^v = \pi r_f^2 \quad \text{if } A_f^p < 1 \quad (17)$$

385 to prevent overestimation. From (15), in the general case, both
 386 distance o_{ij} and frontel radius r_f are required to compute area
 387 A_f^v and then gain γ_{ij} . In this work, the frontel radius is con-
 388 stant, as shown in Section III-A. However, our approach can be
 389 extended to a variable frontel radius by computing gain γ_{ij} in
 390 the fragment shader, where the radius is available.

391 IV. EXPERIMENTS

392 A. Experimental Setup

393 The experimental setup (Fig. 4) includes an industrial robot
 394 arm (Comau SMART SiX) with six degrees of freedom. A
 395 Kinect sensor is mounted on the end-effector and calibrated
 396 with respect to the robot wrist. KinFu egomotion tracking is
 397 disabled and the sensor position is computed from robot for-
 398 ward kinematics. The workspace is a square of about $2.5 \times$
 399 2.5 m that encompasses two tables in front of the robot (high-
 400 lighted in yellow in Fig. 4). KinFu TSDF volume side is set to
 401 to $E = 1.5$ m and the edge resolution is set to $c_{\max} = 512$ cells.
 402 Therefore, the voxel edge length is set to $e = 2.9$ mm, and thus
 403 $r_f = 5.1$ mm. As E is lower than the workspace size, shifting
 404 operations must be performed while scanning different regions
 405 of interest. The same shifting operations must be simulated in
 406 the view evaluation phase, to accurately predict information
 407 gain. Each experiment is performed as follows. First, the robot
 408 scans the environment on a predefined path using KinFu. POIs
 409 are given as input to the system, located near the objects to be
 410 scanned. Regions of interest are initialized as unknown around
 411 each POI as described in Section III-B. Viewpoints are sampled

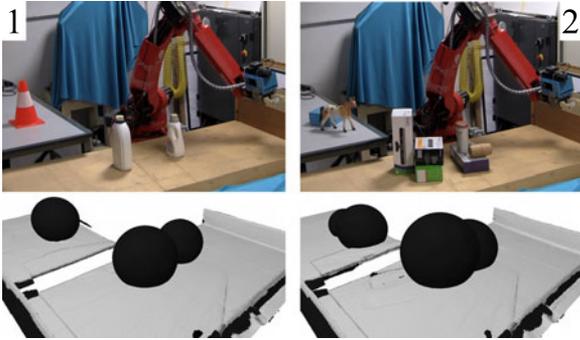


Fig. 5. Top: scenarios 1 and 2. Bottom: the spherical regions of interest centered at each POI, surrounded by black frontals.

TABLE I
EXPERIMENT INITIAL DATA

Scenario	1	2
Initial surfels	~519k	~489k
Initial frontels	~275k	~302k
Initial unknown	~4309k	~7608k

412 on spheres around each POI, at a fixed distance of 0.8 m. Each
 413 POI generates 960 candidate views, sampled at regular intervals,
 414 by varying latitude (10 intervals), longitude (12 intervals) and
 415 rotation around the sensor axis (8 intervals). Then, the NBV task
 416 is started. At every iteration, all viewpoints generated for each
 417 POI are evaluated by the NBV algorithm. The MoveIt! ROS
 418 framework is used for planning a collision free path towards the
 419 viewpoint with the highest predicted information gain. A
 420 collision map with precision 5 cm is extracted from KinFu to
 421 update the MoveIt! planning scene. The collision map considers
 422 both occupied and unknown voxels as obstacles. Viewpoints are
 423 attempted in decreasing score order, until the planner succeeds.
 424 The robot then moves the sensor in the selected NBV pose and
 425 new information is acquired. The Kinect is slightly tilted ($\pm 5^\circ$)
 426 to remove artifacts that otherwise would appear due to the emit-
 427 ted IR pattern. Indeed, if the sensor is fed multiple images from
 428 the same viewpoint in a static environment ripples appear in the
 429 3D reconstruction. The Kinect depth image has a resolution of
 430 640×480 pixels, with a focal length of about 528 pixels. How-
 431 ever, when the sensor is simulated during NBV computation a
 432 560×540 resolution is adopted, with the same focal length.
 433 The simulated camera height is increased to account for the
 434 tilting motion of the real sensor during acquisition, while the
 435 simulated camera width is reduced due to sensor calibration.
 436 The software runs on an Intel i7-6700 CPU at 3.40 GHz, 32 GB
 437 RAM, NVIDIA GeForce GTX 980 Ti GPU, 6 GB RAM.

438 Experiments were performed in two different scenarios,
 439 shown in Fig. 5. In the first scenario, three POIs were defined,
 440 one for each object, with radius 0.2 m. In the second scenario,
 441 four POIs of different sizes were defined, one for each group
 442 of objects. Table I reports the initial number of surfels, frontels
 443 and unknown voxels inside the POIs. In each scenario, the ex-
 444 periment was repeated three times, by changing the NBV score
 445 function. The first score function, named RCV (Ray Casting
 446 Voxel count), is the standard NBV algorithm that maximizes

TABLE II
AVERAGE EXECUTION TIME (SECONDS)

Phase	RCV	RCP	SRP
Initialization	-	-	0.02 ± 0.01
Shifting	2.83 ± 0.17	2.81 ± 0.18	-
Rendering	-	-	0.25 ± 0.03
Ray casting	1.49 ± 0.18	1.11 ± 0.12	-
GPU download	1.29 ± 0.04	0.34 ± 0.00	0.71 ± 0.04
Score computation	3.53 ± 0.15	0.56 ± 0.04	0.46 ± 0.02
Total	9.14 ± 0.41	4.83 ± 0.25	1.43 ± 0.06

447 the number of unknown visible voxels. KinFu ray casting was
 448 exploited to obtain o_{ij} and voxel index c_{ij} for each pixel. To
 449 prevent the same voxel index to be counted more than one time,
 450 a support boolean 3D matrix is used to track which voxels have
 451 already been counted. The matrix has the same size of the TSDF
 452 volume and it is indexed by c_{ij} . The second NBV score func-
 453 tion (RCP: Ray Casting Pixel gain) exploits KinFu ray casting
 454 to compute the pixel values o_{ij} . The distance $|o_{ij}|$ is obtained
 455 as the depth of the intersection between the ray and the first non
 456 empty voxel. Gain γ (14) is used to evaluate the next best view.
 457 RCP only requires knowledge of the pixel values o_{ij} . Finally,
 458 the third score function (SRP) uses pixel values o_{ij} obtained by
 459 surfel rendering as proposed in Section III-C. The NBV is again
 460 estimated by γ . The robot task terminates either when the NBV
 461 predicts a gain lower than a threshold or after 10 robot poses.
 462 The threshold was set as $\gamma_{th} = 0.002 \text{ m}^2$ for RCP and SRP. In
 463 the RCV case, as the area of a voxel face is approximately
 464 $(2.9 \text{ mm})^2$, the threshold was set equal to $0.002 \text{ m}^2 / (2.9 \text{ mm})^2$
 465 ≈ 237 voxels.

B. Results

466 Average execution times of each phase of NBV evaluation are
 467 reported in Table II, as well as standard deviations. Results were
 468 obtained by averaging the evaluation time of each POI (960 view
 469 poses). More than 50 POI evaluations were executed for each
 470 approach in the reported experiments. It can be noticed that the
 471 total time to evaluate 960 poses is 9.14 s for RCV, 4.83 s for RCP
 472 and 1.43 s for SRP. That is, surfel rendering (SRP) outperforms
 473 both volumetric approaches (RCV and RCP) since rendering
 474 is faster than ray casting. The proposed NBV approach based
 475 on surfel rendering (SRP) requires a short initialization phase,
 476 since clouds Σ and Φ are reloaded from RAM to GPU memory.
 477 For the methods based on KinFu ray casting, instead, the TSDF
 478 volume must be shifted and centered on the current POI. There-
 479 fore, the shifting operation delays NBV computation by 2.81 s
 480 on average. SRP improvement is partially offset by the shorter
 481 data download time of RCP, probably due to better CUDA opti-
 482 mization. In general, the RCV approach is the slowest, since it
 483 also downloads voxel index c_{ij} . Moreover, in RCV each voxel
 484 must be counted only once, thus requiring a more complex score
 485 computation method.
 486

487 The surfel/frontel generation procedure introduces a low over-
 488 head at each KinFu shifting operation during 3D reconstruction.
 489 Indeed, shifting lasts for additional 132 ms on average, over a
 490 total time of about 781 ms. The amount of unknown voxels

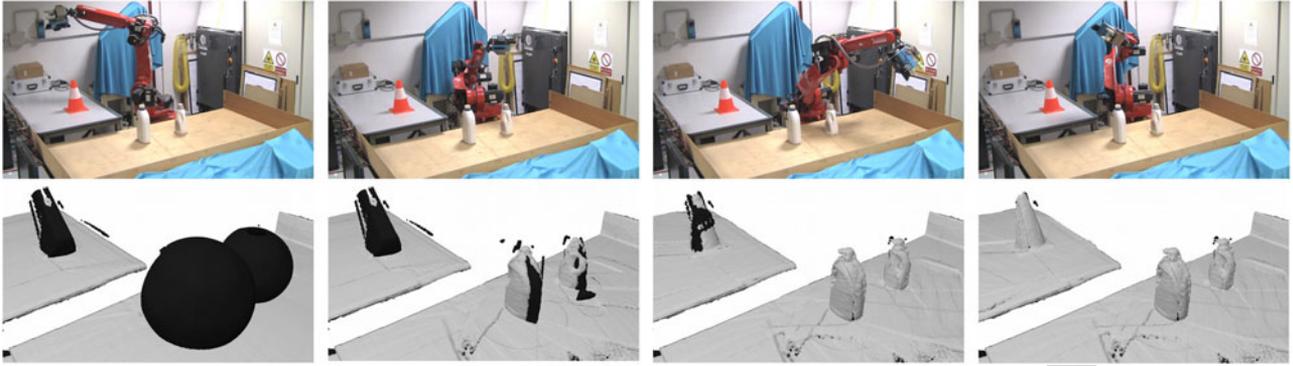


Fig. 6. Top: the first, third, fifth and seventh NBV reached by the robot in the SRP experiment of scenario 1. Bottom: the surfel- and frontel-based representation after each NBV.

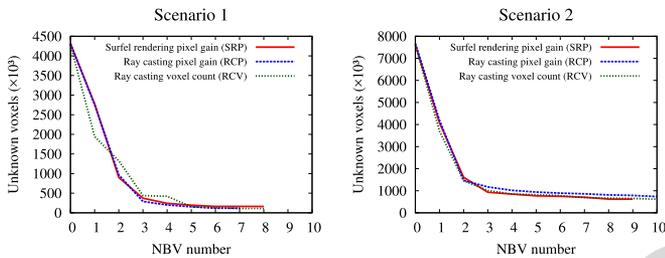


Fig. 7. Number of unknown voxels inside regions of interest, after each NBV.

TABLE III
NBV ITERATIONS, COMPLETENESS AND RECONSTRUCTION QUALITY

Scenario	1			2		
	RCV	RCP	SRP	RCV	RCP	SRP
Iterations	8	7	8	10+	10+	9
Completeness	96%	94%	96%	92%	93%	90%
Average Q_t	425.2	411.3	408.5	531.0	514.7	477.3
Q_t Std. dev.	294.7	249.3	295.5	495.6	385.7	428.7

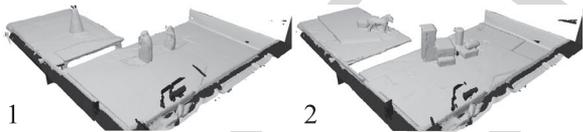


Fig. 8. Surfel- and frontel-based reconstruction at the end of the SRP experiments, for each scenario.

491 inside regions of interest decreases with the number of NBV
 492 iterations, as the robot explores the unknown regions. Fig. 6
 493 shows images of some next best views for SRP in scenario 1, as
 494 well as the progressive reduction of unknown space surrounded
 495 by frontels (in black). The graphs in Fig. 7 show the number of
 496 unknown voxels as the NBV task progresses. All three methods
 497 have a similar trend. Table III reports the number of NBV iter-
 498 ations for each experiment. Symbol 10+ marks experiments that
 499 where stopped after 10 iterations. The final 3D environment re-
 500 construction for the surfel-based experiments is shown in Fig. 8.
 501 Reconstruction quality was assessed by comparing results of the
 502 NBV task with the initial scan of the environment. The initial
 503 robot scan was performed along a predefined path to scan all
 504 POIs and, therefore, it acts as ground truth. We define T the ini-



Fig. 9. Effect of the volume padding on frontel generation, during first NBV of scenario 2. Left: KinFu output, with the TSDF volume limit highlighted in red. Center and right: surfels/frontels before and after the NBV.

tial point cloud produced by KinFu marching cubes algorithm 505
 after the initial scan, inside the regions of interest. Moreover, we 506
 define G the set of all points acquired by Kinect during an exper- 507
 iment. Quality Q_t of point $t \in T$ is defined as the number of 508
 points in G whose distance to t is lower than 2 cm. The meaning 509
 of Q_t is that automated NBV reconstruction quality is higher the 510
 more points are closer to ground truth points obtained in a full 511
 scan of the POIs. Completeness of reconstruction was evaluated 512
 as the fraction of points where $Q_t > 0$. Completeness, average 513
 quality across all points in T and quality standard deviation are 514
 reported in Table III. In general, completeness is comparable for 515
 the three methods. Quality is slightly lower for RCP and SRP 516
 than for RCV, which is probably due to the use of an approxi- 517
 mated gain, as presented in Section III-D, instead of the exact 518
 number of voxels. Fig. 9 shows the effect of volume padding 519
 on frontel generation, as described in Section III-A. The sensor 520
 is oriented towards a POI centered on the small horse object. 521
 However, other POIs are also visible. No data can be acquired 522
 outside the TSDF volume, as highlighted by the red line near 523
 the boxes. Therefore, the unknown regions surrounding the two 524
 POIs on the boxes are only partially carved. Frontels are cor- 525
 rectly generated on the surface of the TSDF volume inside the 526
 spheres. The methods SRP and RCP generate a slightly differ- 527
 ent simulated image o_{ij} , due to the different approximations 528
 made by the two algorithms. An example is shown in Fig. 10. 529
 RCP shows some drawback: the step of the KinFu ray casting 530
 algorithm is larger than the size of a single voxel, therefore, thin 531
 unknown volumes may be skipped during ray casting, as in the 532
 area highlighted with yellow squares. Moreover, some borders 533
 appear jagged (yellow circle), as the algorithm may detect the 534
 unknown space up to one step deep inside the surface. On the 535

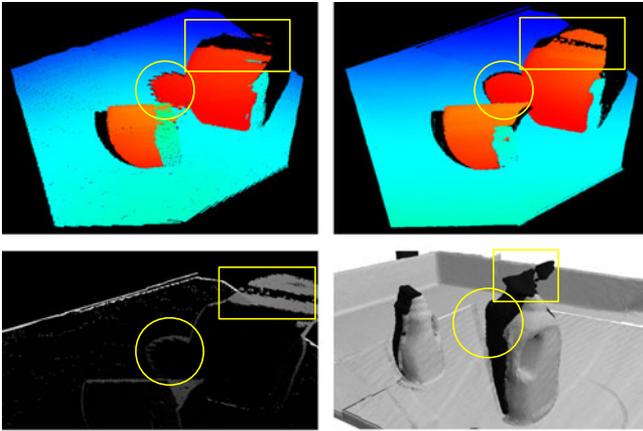


Fig. 10. Top: visible points simulated by RCP (left) and SRP (right) for the third NBV of the SRP experiment in scenario 1. Blue colors represent positive values of o_{ij} , while orange colors negative values. Bottom left: difference between the two simulated images. Bottom right: the surfel-based representation observed from a different viewpoint.

536 other hand the surfel-based approximation of SRP causes ob-
 537 jects to expand slightly, since the surfel/frontel sizes $r_s = r_f$
 538 were over-estimated in Section III-A.

539 V. CONCLUSION

540 In this work a novel method for robot next best view planning
 541 has been proposed. The approach is based on a surfel repre-
 542 sentation of the environment. Surfel rendering is used for NBV
 543 evaluation, instead of complex ray casting operations. Results
 544 indicate that a score function based on surfels is more efficient
 545 to compute and that it achieves comparable results in terms of
 546 reconstruction quality and completeness. Another advantage is
 547 that surfel-based NBV planning can be applied in larger envi-
 548 ronments. A limitation of the proposed method is that it still
 549 requires an initial voxel based volume representation, which is
 550 obtained through KinectFusion, from which surfels and frontels
 551 are extracted. In future work we plan to investigate algorithms
 552 for surfel and frontel generation that do not require an initial
 553 voxel representation of the environment.

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