3D BARRIER-FREE VERIFICATION FOR WHEELCHAIR ACCESS

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ABSTRACT: *This paper proposes a new methodology for identifying barriers encountered by wheelchair users in daily life spaces. Currently, barrier-free designs are required not only for newly constructed buildings, but also when renovating existing facilities and public spaces. However, the arrangement of furniture, equipment, and many other objects in a space often impose barriers, and even the simple bumps and steps on pathways can obstruct wheelchair passage. Furthermore, it is often difficult for administrators to envisage the full reality of barriers in their facilities because potential obstacles can be created inadvertently by a variety of objects that have complicated three-dimensional (3D) geometries. In such cases, their existence will normally remain unknown until someone actually tries to transit the area using a wheelchair. Our approach aims to capture the overall dimensions of target spaces by collecting and combining depth images taken using a hand-held RGB-D camera (also commonly referred to as a ranging camera), and then to navigate a virtual wheelchair through the target space in a computer simulation to check for obstacles. The practical egomotion capabilities of RGB-D camera sensors within actual environments make it possible to achieve real-time simultaneous localization and mapping (SLAM) functionality, which is necessary for creating accurate 3D location maps. The Microsoft Kinect™ sensor, which was originally designed as a user interface for home-use video games, is a good example for a low-cost, compact RGB-D camera. Since the Kinect device is sufficiently compact for use when capturing arbitrary objects in situ, we adopted it for use in our study and applied a SLAM technique to perform barrier checks. Our simulation employs 3D projections of all objects and wheelchair transit volumes onto a floor plane in order to detect potential obstacles. We implemented our proposed method on a laptop personal computer (PC) and collected data from actual classroom and common space locations in a university. The experimental results of our method showed effective functionality in terms of practicality and usability.*

KEYWORDS: *Wheelchair user, Barrier-free, RGB-D camera, Free-hand scan, Obstacle check, 3D model*

1. INTRODUCTION

1.1 Background

The rapidly increasing number of elderly people in society together with the declining birth rate has become a serious issue in Japan. Furthermore, society is expected to be as accommodating to those with physical handicaps as it is to people without such handicaps and is working on overcoming numerous barriers. For example, newly built buildings and facilities are progressively being designed to be barrier-free, and there are ongoing efforts to renovate residential and daily life environments in order to provide easy access to schools, shops, and other public places for wheelchair users. However the continued existence of the barriers that remain in pre-existing facilities highlight the inconveniences faced by wheelchair users as they attempt to move around in society.

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Fig. 1: Example of on-site check for accessibility by a wheelchair user (Kumagaya City Homepage)

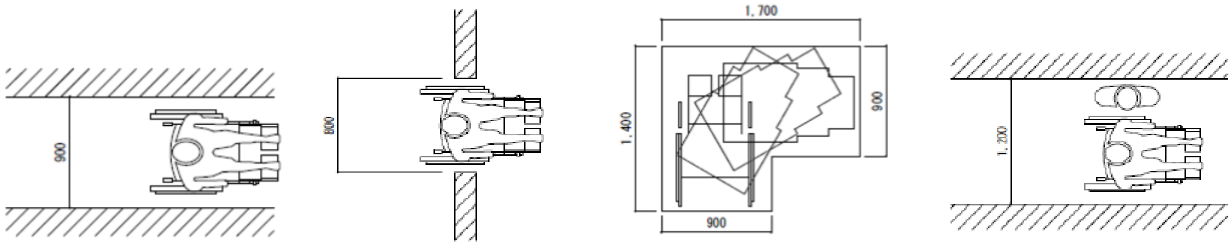
As a side issue, by providing information on the locations of restrooms equipped to service the physically challenged as well as the location of uneven surfaces on pathways, barrier-free maps are gradually becoming familiar as informative tools for elderly people and wheelchair users. In recent years, such maps have been provided on the Web as well as in published form, such as incorporation into booklets. However, the concept of barrier-free mapping is still in the development stage and oftentimes such maps are designed from an administrator's preconceptions rather than from a user's viewpoint. Additionally, while the barrier-free information on such maps is often expressed with specific pictograms designed by industrial standard bureaus or ministries, there are also numerous unique pictograms created and used by local governments, and there has been little effort to date to achieve uniformity. Furthermore, information regarding barrier information details and the investigative methods used to confirm the validity of barrier-free maps differ from place to place. As a result, the barrier-free maps themselves are not always trusted by their intended users.

This paper focuses on the investigative methods used to detect barriers to wheelchair users. We begin by acknowledging that administrators face difficulty in fully comprehending potential barriers in their facilities, especially since many spaces are filled with a variety of objects with complicated three-dimensional (3D) geometries, unless they bring in an actual wheelchair and user into the space to physically verify accessibility (see Fig. 1). As a result, one of the major difficulties involved with existing barriers is the labor cost related to identifying such barriers and determining the degrees of difficulty they impose. Manual inspections are supposed to be conducted by the care-managers or environmental welfare coordinators responsible for evaluating such barriers, and efforts are expected towards the redesign and renovation of existing buildings and facilities into barrier-free environments.

This paper proposes an effective method for investigating the existing physical barriers for wheelchair users that utilize an RGB-D camera, which is capable of compiling depth image information on physical locations. The contact-free and speedy measurement capabilities of RGB-D cameras make it easy to collect onsite information on geometric conditions, and then to compile this data into digitized 3D models. Those 3D environmental models can then be examined in various ways to detect obstacles, and thus eliminate the need to actually bring a wheelchair and user to the target site.

1.2 Mobility and transferring conditions for wheelchairs

To allow wheelchair users free and unencumbered access, a certain amount of space is required for the user's body, hands, and arms when maneuvering the wheelchair. This requirement is in addition to the width of the wheelchair base itself. Referring to the Japanese Industrial Standards (JIS), for example, regulations call for pathway widths of more than 90 cm and doorway widths of more than 80 cm in order to ensure wheelchair accessibility. However, turning a wheelchair also requires a specific minimum space, and it is also important to consider normal two-way pedestrian traffic in public spaces to ensure that sufficient space is available for passing when necessary. Furthermore, it is necessary to ensure that pathway surfaces are sufficiently smooth, and that any slopes are gradual, with specific design elements incorporated if there are differences in floor heights (Osaka Association of Architects & Building Engineers, also see Fig. 2).



(a) (b) (c) (d)

Fig. 2: Fundamental spatial conditions for wheelchair mobility: (a) basic pathway width, (b) doorway, (c) turning space requirements, and (d) passing another person

2. PROPOSED METHOD

2.1 Overview

For comparatively small spaces such as private residences, conducting manual inspections for wheelchair barriers may not require excessive time or labor because the points to be checked are typical and predictable. In contrast, sorting out potential danger spots and barriers in public sites and commercial facilities can be a large-scale job. Furthermore, there is much wider variety in the type and severity of potential barriers. Accordingly, our basic approach involves collecting 3D data on all possible barrier locations with an easy-to-use tool, then conducting in-depth inspections virtually using a personal computer (PC). To realize virtual inspections that match the actual physical conditions of the site in question, we employ an RGB-D camera and an effective registration technique as a 3D captor system. RGB-D cameras can take depth images and send them

to a host PC in real-time, which is suitable for implementing simultaneous localization and mapping (SLAM) techniques (Newcombe et al. 2011). The depth images are aligned with each other using a shape matching process (Chen and Medioni 1992), as well as for estimating the camera position and orientation so that the target location can be captured by a series of different angle frames, each of which has a limited field of view (FOV). The aligned depth image has a 3D mesh surface with the same geometry and the scale of the actual scene. Within the 3D mesh, we can then check the point-to-point distances and the volume sizes of the open spaces while comparing them to the size of a wheelchair and its motion trajectories. The conditions described in the previous section can be taken into account, since the conditions can be expressed on a two-dimensional (2D) map subset of our 3D map geometry.

This framework is similar to the performance-based approach for the wheelchair accessible route analysis described by Han et al. (2010). However, whereas Han's method is based on a 2D plan, we started from detailed 3D shape models of actual environments. Using our method, as-built situations and as-is conditions with extra objects including a fixture and fittings, and even temporally placed objects, can be detected as potential barriers. The noteworthy contribution of our method is its ability to preserve the 3D configuration of the potential barrier components in the environment, which can then be simplified via a basic 2D image processing in order to detect potential obstructions between the wheelchair trajectory volume and the surroundings. The entire procedure consists of the following three steps (also shown in Fig. 3):

(1) Modeling wheelchair motion trajectory

(2) 3D map generation of the physical environment

(3) Collision detection between the 3D map and the wheelchair trajectory for finding barriers

2.2 3D Map Generation

To capture the 3D shape of the physical scenes, we employed an RGB-D camera that is capable of imaging depth information. Many RGB-D cameras use an active stereovision method that performs triangulation using a pair of calibrated structured light sources and a camera. While existing infrastructure management practices are designed around laser rangefinders with high precision but low capture speeds (Watson *et al.* 2011, Miller *et al.* 2008, Shih *et al.* 2006), the compact RGB-D camera devices developed to capture human motions as video game user interfaces in recent years can capture depth images at high frame rates (Freedman *et al.* 2010). Accordingly, after evaluating the capture speed and compact size of these devices, we determined it would be possible to use one as a portable on-site investigation tool. Table 1 shows the specifications of the Kinect™ sensor RGB-D camera used in our implementation and experiments. We also utilize a point cloud library (PCL), an open source SLAM technique implementation, for constructing 3D maps.

Table 1. RGB-D Camera Specification

Device	Kinect™ for Xbox 360
Field of view	57° (H) × 43° (V)
Depth image size	640 pix (W) × 480 pix (H)
Depth range	0.8 ~ 4.0 m
Frame rate	30 fps

2.3 Wheelchair Trajectory Model

To enable virtual inspections on a PC, it was first necessary to model wheelchair performance so that it could be incorporated into the collected 3D environment. The wheelchair model requirements include all possible spatial volumes the wheelchair and user would occupy in 3D space while simultaneously considering the actual size of a wheelchair carrying a user based on the JIS T9201 industrial standard (see Fig. 4), as well as the minimum volume of space required for the wheelchair's trajectory through the target location. The four steps of the modeling process are provided below:

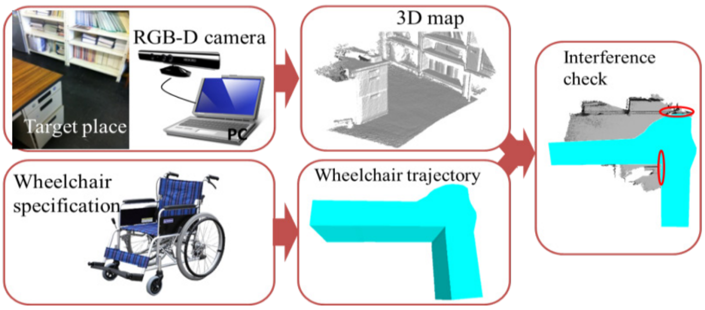


Fig. 3: Conceptual overview of the proposed method

1. A bounding box circumscribing the wheelchair and the user is settled as shown in Fig. 5(a). The height of the box is set to include the user instead of just the wheelchair.

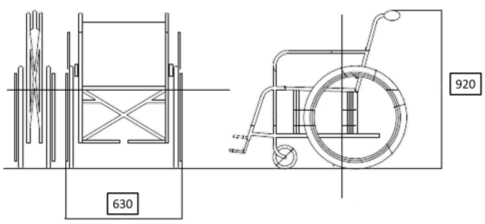


Fig. 4: Standard size of the wheelchair for adults based on JIS

2. The bounding box is moved using translation and rotation. The rotation axis is set to the center of the inner tire, as would occur in the case of an actual wheelchair user making a turn without reverse rolling.

3. The corner positions of the bounding box are recorded during the motion, after which a wire-frame of the trajectory is plotted (Fig. 5 (b)).

4. Finally, the redundant coordinates are removed from the wire-frame and the surface mesh is generated (Fig. 5 (c)).

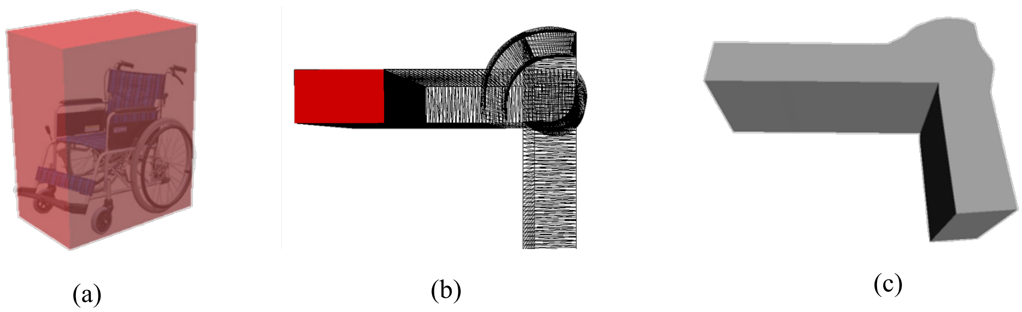


Fig. 5: 3D Volumetric trajectory model of a wheelchair for a right-angled turn: (a) static volume of wheelchair with a user, (b) schematic wire-frame for the movement, and (c) final polygonal model

2.4 Barrier Investigation in 3D Map

2.4.1 Checking the Uneven Surface from the Depth Data

Since the highest floor level difference a wheelchair user can traverse while unassisted is approximately 0.02 m, we tested the ability of our methodology to capture this floor height difference using a Kinect™ sensor. Taking

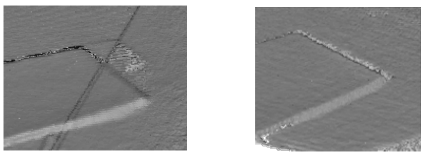
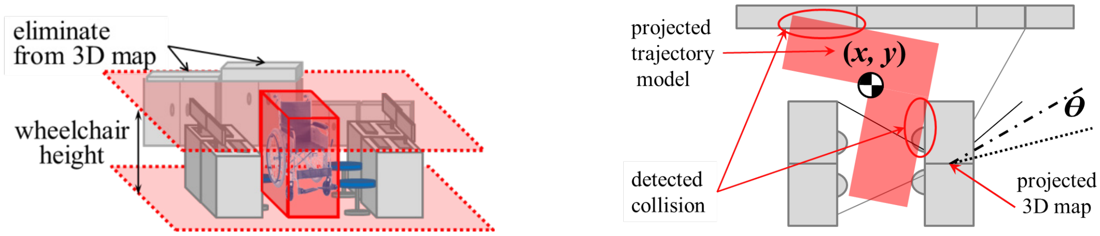


Fig. 6: Example of detected height difference (0.02 m) on the floor: looking down the height gap from 0.7m height at 30° (left) and 60° (right) of view directions

photos within a distance of 0.7 m and within the view direction range of 30° to 60°, the 0.02 m height difference was captured clearly and point-to-point measurement of the gap size was also recorded (Fig. 6)

2.4.2 Barrier Inspection by Collision Detection

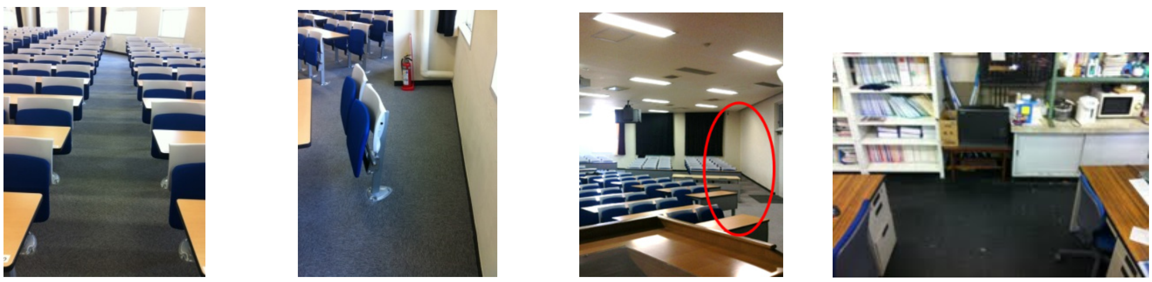
Merging the measurement-based target environment 3D map with the wheelchair trajectory model enables potential physical barriers to be investigated. This process can be accomplished in a straightforward manner by detecting collisions between the 3D map and the trajectory model. However, since both of the modes consist of numerous polygon surfaces, it is still necessary to navigate the trajectory model completely through the 3D map in order to determine whether it can be accomplished without any collisions or contacts between the two. Previously, collision detection techniques developed in the computer graphics field have focused primarily on generating realistic 3D scenes, especially for video games, that require a fast response to contacts between objects. In video games, objects are designed with the smallest number of polygons possible in order to enable the collision detection process to work well. In contrast, depending on the complexity of the location, the number of polygons our 3D map must handle can range from hundreds of thousands to several million.



(a) (b)

Fig. 7: Barrier detection scheme: Within the limit of the wheelchair height (a), 3D map and trajectory modes are projected on to 2D plane, on which collisions are detected as overlapped regions (b)

Accordingly, it was necessary to simplify this collision detection workload by projecting the 3D map onto a 2D space. This was made possible by taking into consideration the point that the wheelchair trajectory will always remain in contact with the floor, and that any possible physical barriers will exist within the height range of the wheelchair and the user. An example of eliminating polygons higher than the wheelchair user in the 3D map and for projecting the remaining polygons onto the floor surface is shown in Fig. 7 (a). The volumetric trajectory model is also projected onto the same surface. Collisions are then detected by the existence of overlapped pixels that belong to both the 3D map and the trajectory model projected onto the 2D plane surface. Again, the clear difference between this method and the method described by Han et al. (2010) is that we started from capturing the environment geometry in situ so that all potential physical obstacles (even those in the air) could be considered during the investigation. Next, the trajectory model is placed at a certain initial position (x_0, y_0) and is translated and rotated within a certain range that covers all possible wheelchair routes within the target location (Fig. 7 (b)).



(a) (b) (c) (d)

Fig. 8: Target positions for experiments at locations (a), (b) and (c) of a large lecture room and (d) of a laboratory

3. EXPERIMENTS

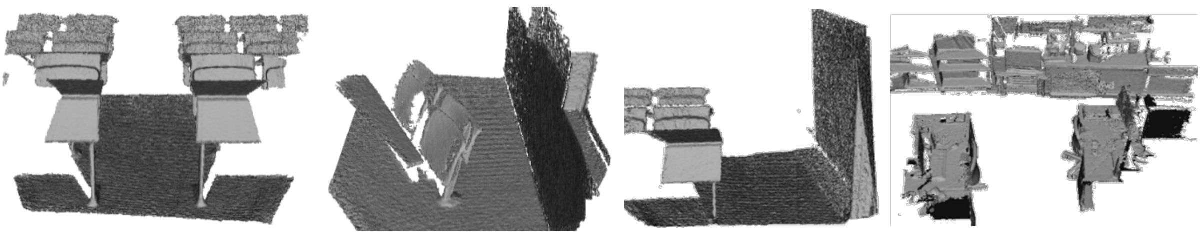
Experiments were then conducted on the campus of our university where there are a number of wheelchair users attending as students. Two locations were picked for our investigation: a typical large lecture room and a comparatively small laboratory space, as shown in Fig. 8. Figure 8 (a) shows a normal pathway between the desks arranged in straight lines. Figures 8 (b) and (c) show a space between a wall and the fold-up chairs, the arrangement of which are not parallel with each other.

Figure 8 (a) also shows a narrow path between the bookshelves, desks, and chairs in a laboratory. Although the arrangement of these items is quite simple, the bottoms of the legs and the desktops themselves cover different amounts of space relative to the floor surface, so determining the narrowest part of the pathway is sometimes difficult. Furthermore, quantitatively estimating the space required to navigate a wheelchair through a particular spot is quite difficult without an actual wheelchair and the user. Figure 9 shows the 3D map created from the captured depth map from each scene shown in Fig. 8. As can be seen in Fig. 9, an overview of Figs. 8 (a) to (c) could be captured in a single shot of the Kinect™ device. The grid size of the voxels needed to register the depth maps was just a 5 mm cube. Figure 9 (d) was constructed by registering six sets of depth data that were obtained from different viewpoints. Among these 3D maps, the smallest model (0.3 million polygons) was found in (c), while the largest model (2.6 million polygons) was found in (d). Figure 10 shows the barrier investigation results. As can be seen in the figure, the desk and chair pathways in Figs. 10 (a) and (b) form complete barriers that prevent wheelchair passage via any route. In contrast, in the case of Figs. 10 (c) and (d), it turns out that no barriers to wheelchair navigation exist. On each image plane, the image size is 640 × 480 pixels, each of which is equivalent to a physical size resolution of 9 × 9 mm.

4. CONCLUSION

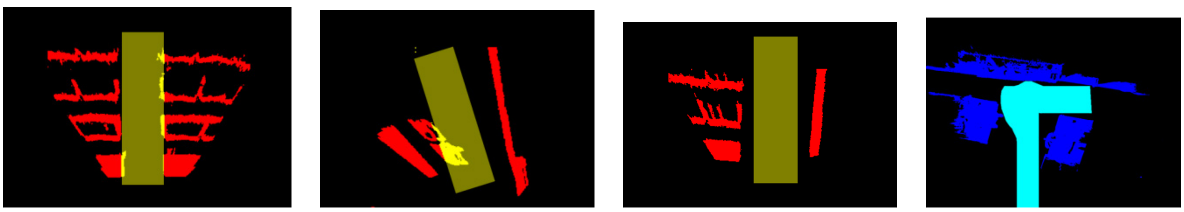
In this paper, we proposed a new method for detecting physical barriers to wheelchair navigation in existing environments. By utilizing a compact RGB-D camera, collecting 3D shape data of the target locations was fast and easy. Furthermore, the acquired data contains rich information about potential physical barriers.

We also developed a barrier detection technique based on collision detection on a 2D image space that preserves candidate barrier information in the initial 3D map. From experiments based on actual locations, it was learned that collecting data and determining the existence of obstacles in real world situations via investigations of virtual wheelchair pathways was achievable. The current implementation is separated in two parts: 3D map generation and 2D barrier detection. Our future work involves combining them together as a packaged application. Validation of wheelchair clearance in situations where no obstacles are detected is also within our plan.



(a) (b) (c) (d)

Fig. 9: Captured 3D map: (a), (b) and (c) are target positions for experiments conducted in a large lecture room, while (d) shows an experiment conducted in a laboratory.



(a) (b) (c) (d)

Fig. 10: Barrier investigation results: The desks and chairs in the (a) and (b) pathways impose complete barriers that block wheelchair passage. In contrast, there is no hindrance to wheelchair navigation in (c) and (d).

5. ACKNOWLEDGEMENT

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6. REFERENCES

Kumagaya City Homepage: Kumagaya UD Block (http://www.city.kumagaya.lg.jp/)

Motoda Y., Usami S. and, Ootake R., (2007) *Japan Society of Traffic Engineers (JSCE)Annual Meeting*, Vol. 62. 4-030. (In Japanese)

Osaka Association of Architects & Building Engineers, (http://www.aba-osakahu.or.jp/fukusi) (in Japanese)

Barak Freedman et al. 2010., DEPTH MAPPING USING PROJECTED PATTERNS, US patent, US2010/0118123 A1

Shih, N. and Huang, S., (2006), 3D Scan Information Management System for Construction Management." *J. Constr. Eng. Manage.*, 132(2), 134-142.

Watson, C., Chen, S., Bian, H., and Hauser, E., (2011) LiDAR Scan for Blasting Impact Evaluation on a Culvert Structure, *J. Perform. Constr. Facil.*, 10.1061/(ASCE) CF.1943-5509.0000318.

Miller, P. E., Mills, J. P. Barr, S. L. Lim, M. Barber, D. Parkin, G. Clarke, B. Glendinning, and S. Hall, J., (2008) Terrestrial laser scanning for assessing the risk of slope instability along transport corridors, *XXIst ISPRS Congress: Commission V, WG 3*, 495-500.

Han C. S., Law K. H., Latombe J. C, and Kunz C. J., (2002) A performance-based approach to wheelchair accessible route analysis Original Research Article, *Advanced Engineering Informatics*, Vol. 16, Issue 1, 53-71.

Newcombe A. R., Izadi S., Hilliges O., Molyneaux D., Kim D., Davison J. A., Kohli P., Shotton J., Hodges S., and Fitzgibbon A., (2011) KinectFusion: Real-Time Dense Surface Mapping and Tracking, *IEEE International Symposium on Mixed and Augmented Reality*, 127-136.

Chen Y. and Medioni G. (1992) , Object Modelling by Registration of Multiple Range Images, *International Journal of Image and Vision Computing*, 10(3):145-155.

Point Cloud Library (PCL) (accessed in 2013): http://pointclouds.org/