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Development of a remote accessibility assessment system through three-dimensional reconstruction technology

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Abstract—A Remote Accessibility Assessment System (RAAS) that uses three-dimensional (3-D) reconstruction technology is being developed; it enables clinicians to assess the wheelchair accessibility of users' built environments from a remote location. The RAAS uses commercial software to construct 3-D virtualized environments from photographs. We developed custom screening algorithms and instruments for analyzing accessibility. Characteristics of the camera and 3-D reconstruction software chosen for the system significantly affect its overall reliability. In this study, we performed an accuracy assessment to verify that commercial hardware and software can construct accurate 3-D models by analyzing the accuracy of dimensional measurements in a virtual environment and a comparison of dimensional measurements from 3-D models created with four cameras/settings. Based on these two analyses, we were able to specify a consumer-grade digital camera and PhotoModeler (EOS Systems, Inc, Vancouver, Canada) software for this system. Finally, we performed a feasibility analysis of the system in an actual environment to evaluate its ability to assess the accessibility of a wheelchair user's typical built environment. The field test resulted in an accurate accessibility assessment and thus validated our system.

Key words: 3-D model, 3-D reconstruction, accessibility, built environment, camera, home modification, remote assessment, telerehabilitation, virtual reality, wheelchair.

INTRODUCTION

The number of wheelchair users age 15 and over is estimated at more than 2.2 million in the United States. [1] For any given physical disability, the degree of limitation an individual experiences depends on the quality of his or her social and physical environment [2]. Consideration of the built environment is especially critical for wheelchair users given the potential limitations it can impose. The most effective rehabilitation outcomes are realized when programs consider both functional restoration and environmental modification [2]. The U.S. Department of Housing and Urban Development's 1995 American Housing Survey assessed whether household members had permanent physical activity limitations and, if so, whether home modifications had been performed. Based on the survey, approximately 5.1 million (57.4%) of the households in which at least one member experienced an activity limitation had no home modifications [3]. For mobility devices to be effective, users must modify their environments so they are physically accessible to those devices [4]. In this study, only homes of individuals

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Abbreviations: 3-D = three-dimensional, ADAAG = Americans with Disabilities Act Accessibility Guidelines, CASPAR™ = Comprehensive Assessment Survey Process for Aging Residents, COS = conventional on-site, NASA = National Aeronautics and Space Administration, POTS = plain old telephone system, RAAS = Remote Accessibility Assessment System, VR = virtualized reality.

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who use a wheelchair as their primary means of mobility were considered. The Americans with Disabilities Act Accessibility Guidelines' (ADAAGs') space requirements for mobility are also based on wheelchairs, because people who use crutches, walkers, or canes can travel wherever wheelchair users can [5].

Effective home modification requires consultation with skilled professionals who can assess the home environment and identify the changes necessary for meeting the wheelchair user's needs. Availability of skilled professionals with experience in home modifications for accessibility is limited (http://www.ehls.com). Providing services in rural areas is particularly difficult because such services require extended travel time that increases cost and consumes the limited time of skilled professionals. A system that makes accurate remote assessments possible would improve our ability to perform home assessments easily and at decreased cost.

Some developmental work has been done with a remote assessment system for rural or underserved areas. A team of clinicians at the Shepherd Center (Atlanta, Georgia) performed a case study of remote home-modification evaluation using a videoconference system [6–7]. They demonstrated that remote telerehabilitation assessments could potentially allow specialists to diagnose accessibility problems in home environments and prescribe appropriate modifications, regardless of the location of the client, home, or specialist. Another effort was undertaken by Extended Home Living Services in Wheeling, Illinois, where a remote assessment survey instrument was developed: the Comprehensive Assessment Survey Process for Aging Residents (CASPAR™). The CASPAR™ instrument can be mailed to residents with disabilities in remote areas, and information about their priorities, activities of daily living, and ability to participate in home-specific tasks as well as the space, layout, and design of their residences can be collected and home modifications can be recommended [8–9].

However, both of these studies are limited in that the dimensions obtained are not sufficient for specifying modifications. Both methods depend on dimensions obtained by the client with a tape measure. The Shepherd Center's research team used a low-bandwidth plain old telephone system (POTS)-based videoconferencing system, but the POTS system could not provide sufficient resolution for them to discern the physical objects in detail. Moreover, in addition to the services of a home-modification specialist, the study required a technician skilled at operating videoconferencing equipment who would be paid as much for travel and labor as the home-modification specialist. This additional expense might threaten the cost-effectiveness of the intervention. The CASPAR™ also had limitations: with no three-dimensional (3-D) view of the structure of the built environment, the home-modification specialist still required photographs taken by users or their caregivers.

The term "virtualized reality" (VR) was coined and introduced in a paper by Kanade et al. [10]. The traditional virtual reality world is typically constructed with simplistic, artificially created, computer-aided design models. VR starts with a real-world scene from 2-D photographs and virtualizes it [10].

The computer technology that allows us to develop 3-D virtual environments consists of both hardware and software. The current popular, technical, and scientific interest in virtual environments is inspired in large part by the advent and availability of increasingly powerful and affordable interactive, graphical display systems and techniques [11]. Virtual reality is becoming a practical, affordable technology for the practice of clinical medicine. Modern high-fidelity VR systems have practical applications in areas ranging from psychiatry to surgical planning to telemedicine [12]. In order to build virtualized medical environments, researchers require the technology to create 3-D models from real-world images.

We have entered an era in which the acquisition of 3-D data is ubiquitous, continuous, and massive. These data come from multiple sources, including high-resolution geographically corrected imagery from aerial photography and satellites, ground-based close-up images of buildings and urban features, 3-D point clouds from airborne laser range-finding systems, imagery from synthetic aperture radar, and other sources. To make these data useful, we should employ them to model the real world [13]. The architectural environment is one of the primary areas to which 3-D reconstruction of real-world objects and scenes can be applied. As laser scanning-technology, 3-D modeling software, image-based modeling techniques, computer power, and virtual reality technology advance, the 3-D reconstruction of cultural heritage applications with digitization and modeling becomes increasingly common [14].

A primary goal of computer vision is the reconstruction of 3-D shapes from 2-D visual images. While active methods such as range finding or laser striping are accurate, they require expensive equipment. The problem of cost has motivated the implementation of passive techniques that infer 3-D depth information from one or more 2-D intensity images [15]. Photogrammetry, which loosely translates from the Greek as "light drawn to measure," is the technique of obtaining measurements from photographs and can provide a cost-effective alternative to laser technologies. The use of engineering photogrammetry to achieve extremely accurate 3-D models has become affordable and convenient, with improvements in the processing power of desktop computers and the ready availability of inexpensive, user-friendly image-processing software packages. The range of potential uses of photogrammetry is extensive, with the following applications under active consideration: (1) optimization of equipment siting, (2) production of synthetic environments, (3) refit planning and monitoring, (4) damage assessment and repair, (5) design modification planning and visualization, (6) computer-based and virtual reality training, (7) generation of a visual database of an historic building, and (8) crime scene reconstruction [16].

Therefore, the use of VR technology and telerehabilitation concepts for assessment of the built environments of persons with severe mobility impairments was recently proposed by University of Pittsburgh researchers [17]. The Remote Accessibility Assessment System (RAAS) described here is being developed as part of the proposed project.

We designed the RAAS to evaluate the accessibility of physical environments of wheelchair users with a virtualized 3-D model. The RAAS takes advantage of state-of-the-art digital imaging, 3-D reconstruction, and photogrammetry technologies. The outcome of the assessment depends on the measurement accuracy, which depends on the skill of the person who takes the measurements. The RAAS can potentially overcome limitations of previous studies by providing accurate measurements and allowing the evaluation specialist, architect, or rehabilitation engineer to see the space in three dimensions. The RAAS could produce better results than previous methods because specialists can evaluate the environment with more realistic visual information in addition to numerical data. Nevertheless, accuracy remains a critical concern in the virtualized environment [12], and usability is a primary concern for the telerehabilitation system [18]. Accuracy and usability are thus keys for developing a successful system. We conducted this study to analyze the reliability of candidate technologies.

Specific Aims

Our objective was to choose appropriate cameras/settings and 3-D modeling software for use in the RAAS. In this study, we had the following goals:

1. Investigate the RAAS's capability in terms of accuracy for modeling interior environments.
2. Compare the RAAS's performance with different cameras/settings.
3. Demonstrate the feasibility of applying the RAAS in an actual environment.

Accuracy Analysis

The RAAS requires 3-D reconstruction of the physical environment. We can use laser-scanning technologies as a fast way to acquire accurate measurements of built environments. Although such active methods are accurate, they require specially trained operators and expensive systems like the Leica Geosystems (St. Gallen, Switzerland) high-definition surveying system (http://hds.leica-geosystems.com). Even if the companies provide as-built documentation for the laser-scanning technologies (http://www.quantapoint.com), these methods are too expensive for practical application in individuals' homes [19]. Therefore, we will use photogrammetry technology that constructs 3-D models from 2-D images to model the space in three dimensions.

Several software packages are available that produce 3-D models: PhotoModeler (EOS Systems, Inc, Vancouver, Canada) (http://photomodeler.com), ImageModeler (RealViz, Los Angeles, California) (http://www.realviz.com), and Viewpoint Services (Viewpoint Corporation, New York, New York) (http://www.viewpoint.com). PhotoModeler and ImageModeler are similar products that enable 3-D reconstruction of real scenes or objects from 2-D photographs. ImageModeler has more applications for multimedia than technical projects, while PhotoModeler has many scientific applications and shows evidence of high accuracy. Therefore we chose PhotoModeler Professional 4.0 for this study.

To use PhotoModeler, an operator takes one or more photographs of a scene or object. The photographs are displayed on screen and the operator marks each photograph with the mouse, tracing and tagging features of interest with dashed lines (**Figure 1**). PhotoModeler then combines the data and locates the marked features in three dimensions. The marks become accurately measured points, lines, curves, cylinders, or surfaces in a single unified 3-D space. PhotoModeler uses a special

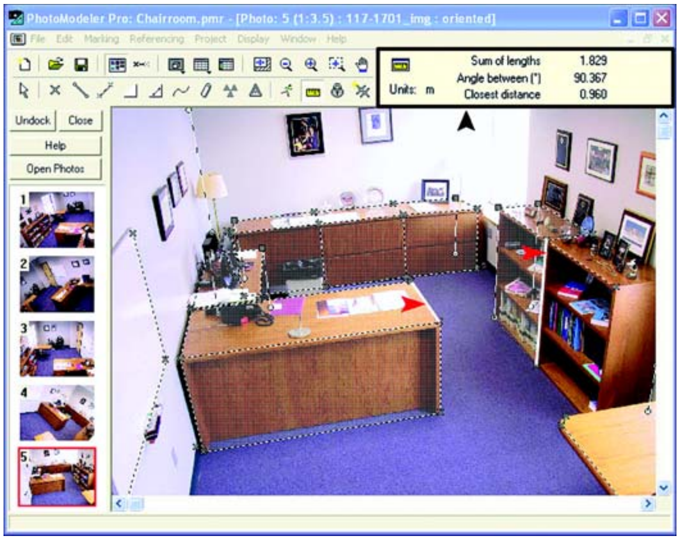

Figure 1.
Marked lines and points on photograph for creation of 3-dimensional model with PhotoModeler software (EOS Systems, Inc, Vancouver, Canada). Red arrows indicate measurement between two points (desk and shelf) and black arrow indicates measurement toolbar.

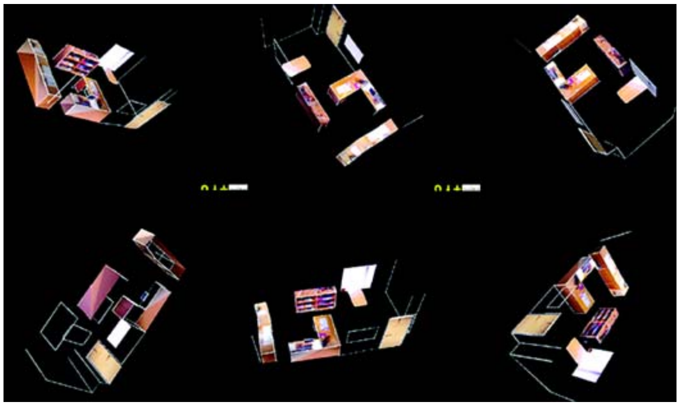

Figure 2.
Rotational views in PhotoModeler software (EOS Systems, Inc, Vancouver, Canada).

numerical algorithm to create a 3-D model from the photographs. After the 3-D model is produced successfully, the software shows all objects that have valid 3-D locations and the view rotates around the arbitrary center of the model (**Figure 2**). Coordinate and distance measurements in different units (meter, foot, centimeter, etc.) are very easy to view. If we click on the lines or points with the measure pointer, the measure toolbar displays measurements of the user-selected set of features (**Figure 1**). Based on our experience, operation of PhotoModeler appears to require no special expertise beyond basic knowledge of computer graphics and design.

Lynnerup et al. used PhotoModeler for an identity verification experiment. The software produced a 3-D wire-frame model based on photographs of human faces. This study showed a high degree of correct exclusion; in 14 of 15 cases, persons were correctly excluded [20]. Vedel used PhotoModeler to construct a 3-D model of Aarhus Cathedral, one of the oldest buildings in Denmark. He also employed PhotoModeler successfully in his work measuring existing buildings to create architectural documentation for renovation and expansion projects [21]. Fedak used PhotoModeler to measure a set of reference points during the construction of a large ship. He worked with a relatively low-cost digital camera and retroreflective survey targets to produce images from which PhotoModeler could then determine accurate 3-D coordinates. His study showed coordinate accuracy on the order of 1:10,000, which is suitable for many applications in architecture and for some industrial measurement applications (http://www.photomodeler.com/pdf/fedak1.pdf). Work at the National Aeronautic and Space Administration (NASA) showed that PhotoModeler has a high accuracy value of 1:2,800 [22].

However, Fedak and the NASA researchers used the software to model the exterior of objects, which differs significantly from our interior environment modeling application. We therefore needed to evaluate and verify the software's capability to produce sufficiently accurate 3-D models for our application.

Comparison of Cameras/Settings

Usability was a primary consideration for the RAAS design. Because the proposed technique of 3-D reconstruction is based on image acquisition, the techniques and logistics involved in acquiring the images are critically important [23]. The process of generating the 3-D model from 2-D images is somewhat labor intensive in that it takes a trained individual about 2 h to generate a model of a typical interior room with four walls. To limit the number of visits to the remote site, we wanted to develop an image-acquisition protocol that could be performed by an untrained individual without direct supervision. The use of expensive and/or sophisticated camera equipment is therefore impractical, even though resolution is the most important factor in camera selection. Such equipment would likely be too complicated for the layperson to use effectively without training and too valuable to risk being lost or damaged by an untrained and unsupervised user. To overcome this problem, we proposed that inexpensive disposable cameras or consumer-grade digital cameras be used on site by untrained individuals, either the users themselves or their caregivers. To study these alternatives, we compared the modeling accuracies of four different cameras/settings: one disposable camera and three digital camera variations [24].

Feasibility Test

After performing the accuracy assessment and comparison of camera/settings, we applied the RAAS to the actual built environment of a wheelchair user to demonstrate its capability for assessing wheelchair accessibility.

Because wheelchair users and their caregivers will not be familiar with the kinds of pictures needed for the 3-D modeling process, we developed a set of comprehensive guidelines that provide instruction on how to take pictures appropriate for 3-D modeling software. After creating several 3-D models of interior environments, we established 10 fundamental rules for taking photographs:

1. Photographs should be taken at a fixed focal length.
2. Reference object should be measured within a target space.
3. Camera should be placed at the highest possible position with the back as close as possible to walls and ceiling.
4. Photographs need not include the ceiling.
5. Each photograph should include the floor and as many objects on the floor as possible.
6. Every point and wall intersection line and every object should be included in at least two photographs.
7. Each photograph should contain as many objects within a target space as possible.
8. Each photograph should contain two or more adjacent walls and two or more vertical wall intersection lines if possible.
9. Objects that can hide the corner point and/or vertical wall intersection line should be removed
10. Blinds or curtains should be drawn to block out extra light.

In this feasibility study, a photographer (friend of the user) was given these instructions before the target home was photographed. **Figure 3** shows an image in the guidelines that illustrates appropriate camera angles.

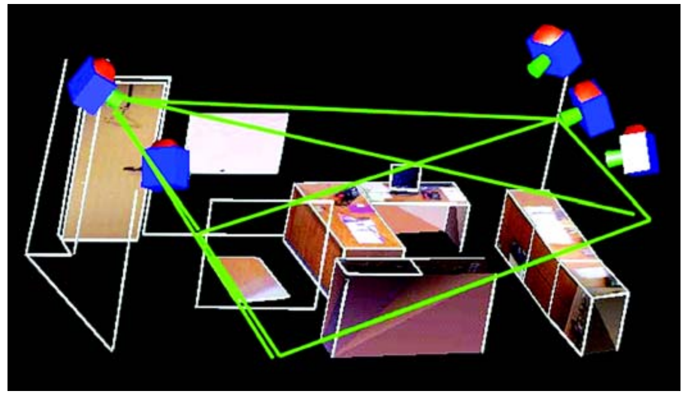

Figure 3.
Appropriate camera angles schematic included in guidelines for instructing wheelchairs users or their caregivers in taking photographs appropriate for 3-dimensional modeling process.

METHODS

Accuracy Analysis

We analyzed the accuracy of dimensional measurements of the virtualized environment of a wheelchair user's office space. The office was 6.5 m × 3 m. We used the Canon G1 (Canon, Lake Success, New York) digital camera with 3.3 megapixel resolution (http://www.canon.com). We calibrated the camera with Camera Calibration 4.0 (EOS Systems, Inc, Vancouver, Canada) software. PhotoModeler uses the focal length, principal point, and digitizing scale of a camera to produce 3-D models from that camera and calculates camera information such as focal length, format-size width, principal point, and lens-distortion parameters with its calibration process (**Figure 4**). From more than 20 pictures that were taken, we selected 5 (**Figure 5**) to use with PhotoModeler for generating the 3-D model of the office space. When taking photographs, we measured the depth of the desk and used that measurement to add scale to the 3-D model of the office. **Figure 6** shows the 3-D model we produced.

To check the accuracy of the 3-D model, we identified six target areas (**Figure 6**): desk width, desk height, side–desk width, width between desk and side bookshelf, width between desk and back drawers, and entrance width. We measured objects with the PhotoModeler virtual measurement tool in the 3-D model environment and with a tape measure in the physical environment.

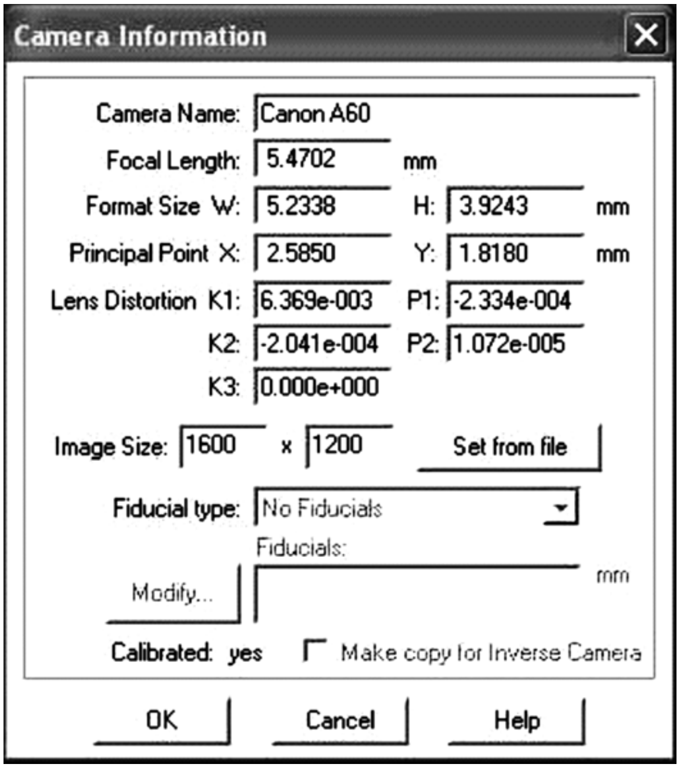

Figure 4.
Information from camera calibration software (EOS Systems Inc, Vancouver, Canada).

Comparison of Cameras/Settings

We compared measurement accuracy for four cameras/settings: a 1.5 megapixel resolution disposable film camera (Giant Eagle, Inc, Pittsburgh, Pennsylvania) (http://www.gianteagle.com), a 1.2 megapixel resolution inexpensive consumer-grade digital camera (Canon A10), a 3.3 megapixel high-resolution digital camera (Canon G1), and a 3.3 megapixel high-resolution digital camera with a wide-angle lens (Canon G1, Canon Wide Converter WC-DC58). We used images from each camera/setting to assess the bathroom of a wheelchair user's home. The test procedure was as follows:

1. Each camera/setting was calibrated with Camera Calibration 4.0 software.
2. A person unfamiliar with the project was instructed how to use each of the four cameras/settings and how to photograph the physical environment to create appropriate 3-D models.
3. Ten or more photographs per camera/setting type were taken of the same bathroom.
4. The dimensions of 10 areas (A–J) of the bathroom were measured manually to the nearest 0.1 cm with a tape measure (**Figure 7**).
5. One 3-D model was created with images acquired from each camera/setting (**Figure 8**).
6. The dimensions of the 10 areas of the bathroom were extracted from the models and compared with the tape-measure measurements.

Feasibility Test

A final feasibility test was conducted with the 1.2 megapixel resolution Canon A10 digital camera. The target environment was a wheelchair user's apartment unit. The wheelchair user's friend was instructed on how to take the photographs. He took 60 pictures; 15 pictures each of the entrance hallway, bedroom, living room, and bathroom.

After the camera was calibrated, we generated a 3-D model for each of the four parts of the apartment, so dimensions of the physical environment could be easily measured in the virtualized environment. **Figure 9** shows the four models that were generated with the modeling software based on 2-D photographs. We used the models to identify problematic points for wheelchair accessibility by checking whether specific tasks could be performed by the wheelchair user.

RESULTS

Accuracy Analysis

The accuracy analysis trial of a wheelchair user's office space showed an average accuracy value of 1:200 (0.51%) (**Table 1**). This degree of accuracy could result in a measurement error of 4 mm (0.16 in.) for a typical 800 mm (32 in.) door opening.

Comparison of Cameras/Settings

Table 2 shows the comparison of measurements of 10 target areas taken from four different 3-D models of the target bathroom. Deviations between each area's measurement as determined by tape measure and each 3-D model were calculated. The model generated from images created with the disposable camera showed the lowest accuracy, 1:39. The models generated from the Canon A10 and Canon G1 camera images produced accuracy values of 1:59 and 1:63, respectively. The model generated from images from the G1 camera with a wide-angle lens showed the highest accuracy, 1:200. The

Figure 5.
Wheelchair user's office space from five angles for accuracy analysis experiment.

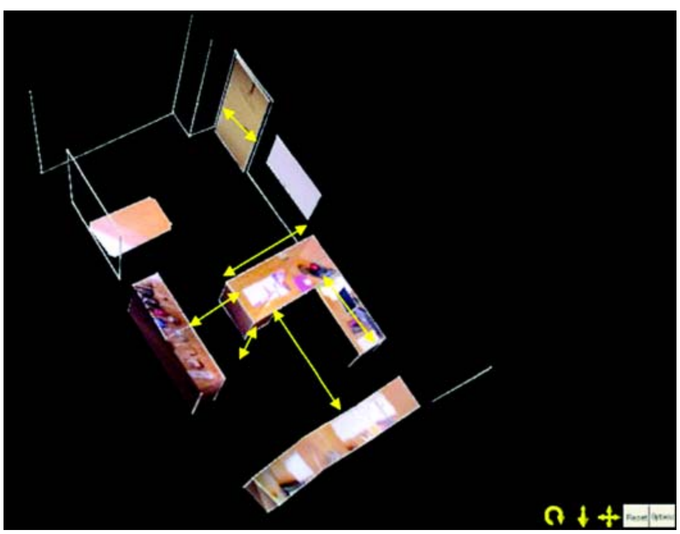

Figure 6.
Target areas to measure in 3-dimensional model of wheelchair user's office for accuracy analysis experiment.

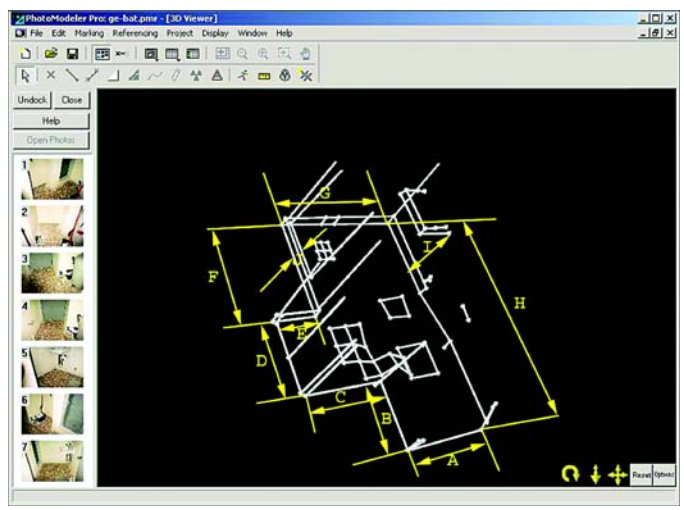

Figure 7.
Target areas to measure in 3-dimensional model of wheelchair user's bathroom for comparison of cameras/settings. Actual and modeled measurements of A–J in **Table 2**.

models generated from the disposable, Canon G1, and Canon A10 cameras required seven photographs. The model generated from the Canon G1 with wide-angle lens required six photographs.

Feasibility Test

Using the 3-D models constructed with PhotoModeler and the 2-D photographs from the Canon A10 digital camera, we discovered that the kitchen and bedroom

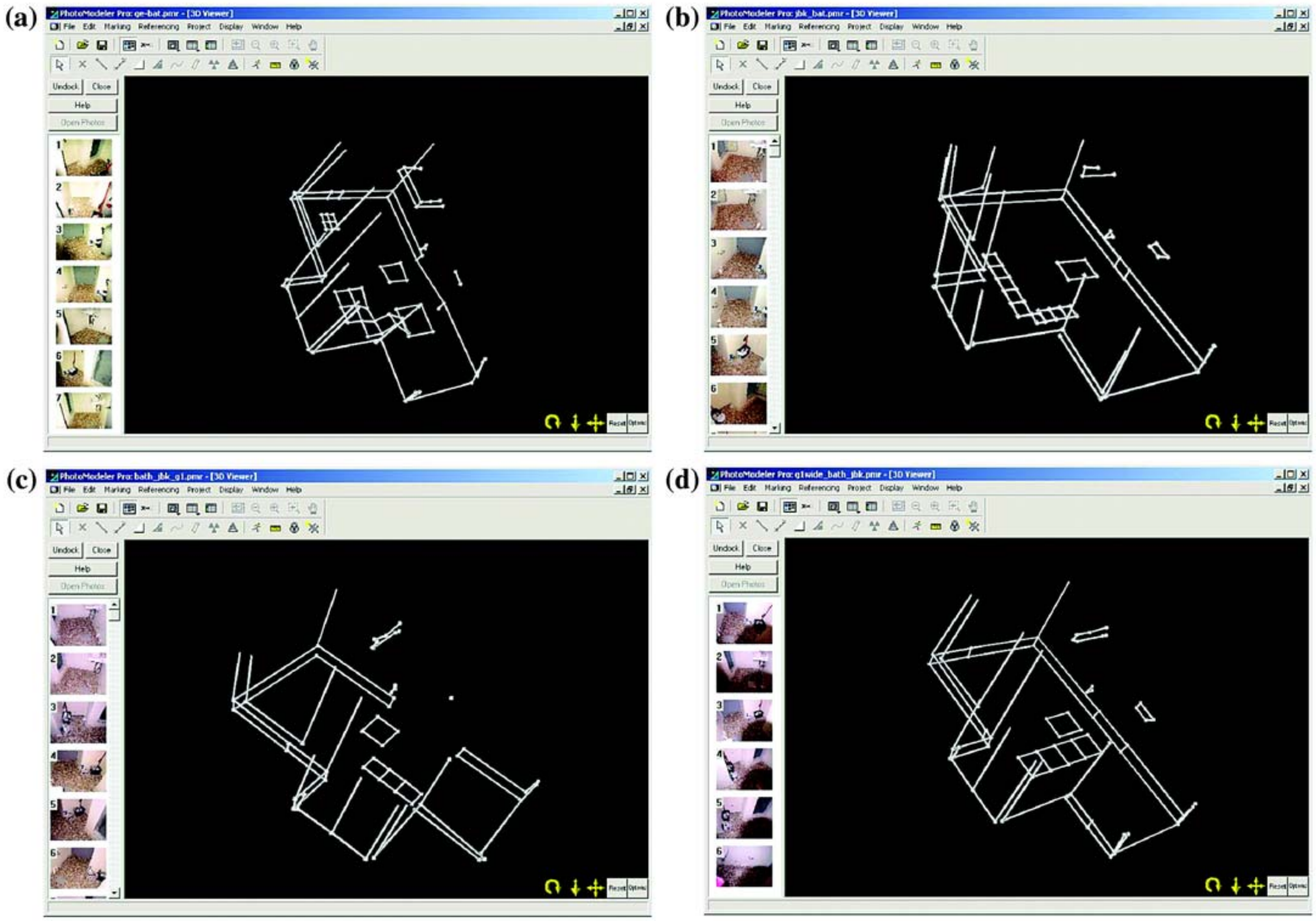

Figure 8.
Digital 3-dimensional models of wheelchair user's bathroom created with photographs from **(a)** disposable camera, **(b)** Canon A10 digital camera, **(c)** Canon G1 digital camera, and **(d)** Canon G1 digital camera with wide-angle lens.

doorways of the wheelchair user's apartment unit should be widened and the shower threshold should be removed and that the bathroom door, entrance door, dining table, and lavatory could accommodate the user's wheelchair. The T-shape turning space of the entry was also accessible according to the ADAAGs (**Figure 10**) and the user's wheelchair dimensions (width: 27 in., length: 44 in., height to knee: 27.5 in.).

DISCUSSION

We recorded the time required to construct the 3-D models in **Table 3**. The time decreased from the first experiment to the second and third experiments. It took too many hours to create the first model because we were not accustomed to using the software. These extra hours included trial and error learning time because the PhotoModeler manual lacks sufficient information on reconstructing interiors of built environments and focuses rather on exterior physical environments and objects. We struggled to take appropriate pictures and figure out how to construct a 3-D model with PhotoModeler. Models in the third experiment routinely required 2 to 4 h to complete. Currently, we can construct a model of a part of a home in 1 to 2 h.

Accuracy Analysis

We expect that objects that appear in three or more photographs will be measured with higher accuracy than will those that appear in only two photographs. No operator can mark a point perfectly, and occasionally the targeted

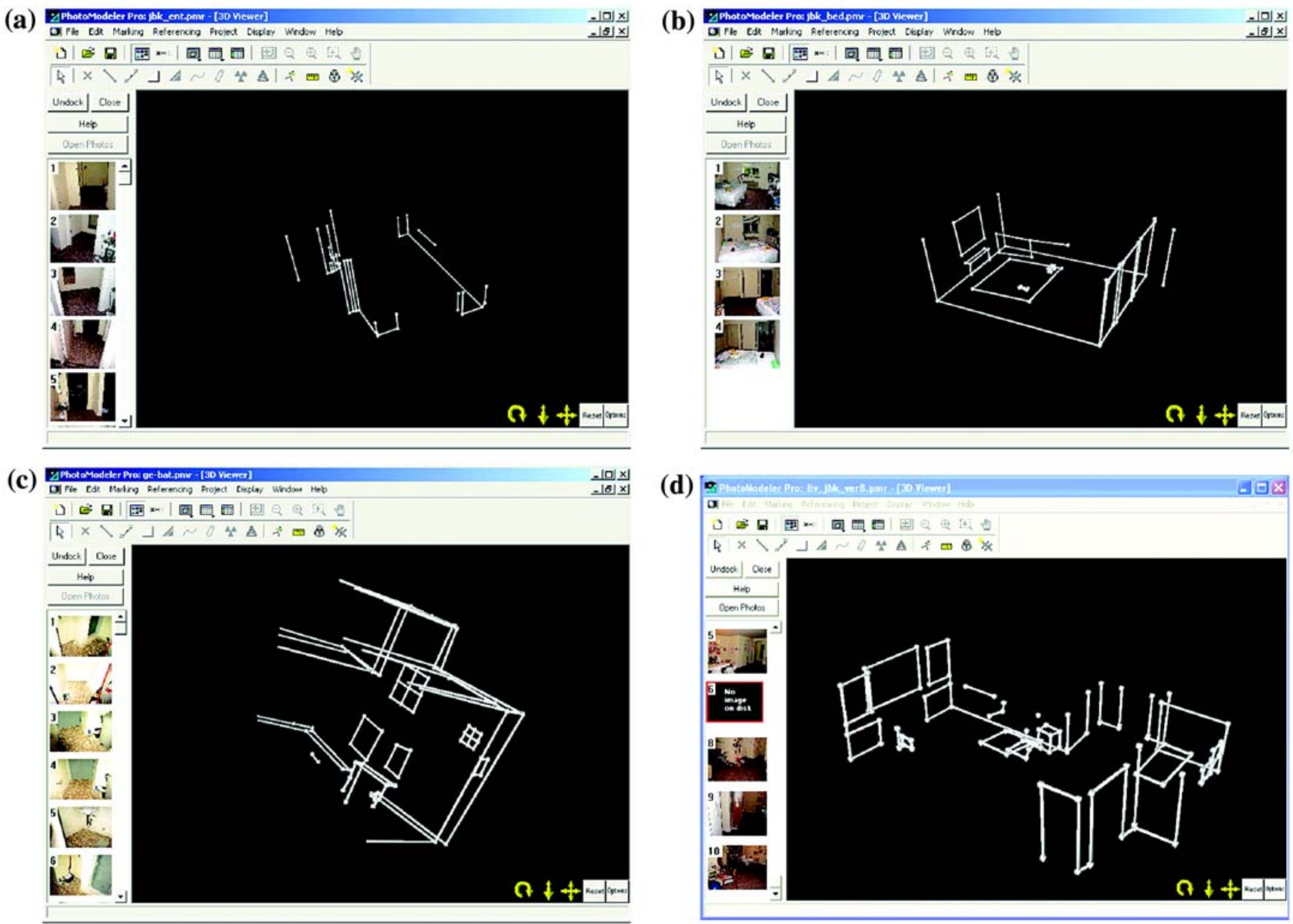

Figure 9.
Digital 3-dimensional models of wheelchair user's **(a)** entrance hallway, **(b)** bedroom, **(c)** bathroom, and **(d)** living room for feasibility test.

point registers as fuzzy or difficult to position exactly in the photograph. If PhotoModeler has good camera station positions but imprecise point locations in the photographs, the projected 3-D point will be inaccurate. To reduce this problem, we mark the desired point in three or more photographs. That way, if the point were positioned incorrectly on one of the photographs, the other two photographs could compensate for it. If it were marked on only two photographs, errors would be undetectable and accuracy in creating 3-D models would decrease.

After the first trial using PhotoModeler, we recognized that the accuracy of the virtualized environment is affected by image quality and by the amount of time and effort the person developing the model commits. We achieved a higher accuracy level in the first experiment than in later experiments because we took more pictures and because our marking and referencing efforts in PhotoModeler were more deliberate. But too many hours were spent on the first experiment relative to later experiments, as we can see in **Table 3**. Later experiments required less time because we had gained experience using the software and because we had developed guidelines for taking photographs. An experienced architect on our research team suggested that an accuracy value of 1:30 is tolerable for assessing wheelchair accessibility. Sanford et al. produced a similar tolerance level in their study [7]. They stated that because all measurements would be field verified by a contractor prior to construction, measurements within ~1 in. during the assessment

Table 1.
Accuracy analysis experiment. Accuracy of actual (tape measure) vs modeled measurements (cm) of six targets in wheelchair user's office space. Measured desk depth = 76.1 cm and base scale = 5.

Target	Actual	Modeled	Deviation	Deviation Ratio (%)	Shared Photographs
Desk Width	167.5	167.4	0.1	0.06	4
Desk Height	73.5	73.2	0.3	0.41	2
Side–Desk Width	122.0	121.1	0.9	0.74	2
Side Way	96.0	95.9	0.1	0.10	3
Back Way	180.5	180.5	0.0	0.00	2
Entrance	91.1	93.6	2.5	2.74	2
Mean	121.8	—	0.7	0.51	2.5

Table 2.
Comparison of cameras/settings. Actual (tape measure) vs modeled measurements (cm) from 10 different areas of the target bathroom. Objects A–J are identified in **Figure 7**.

Object	Actual	Disposable			Canon A10			Canon G10			G1 Wide-Angle Lens		
		Modeled	Deviation	Ratio	Modeled	Deviation	Ratio	Modeled	Deviation	Ratio	Modeled	Deviation	Ratio
A	91.6	92.1	0.50	0.005	92.4	0.80	0.009	93.5	1.90	0.021	91.6	0.00	0.000
B	62.4	66.7	4.30	0.069	64.5	2.10	0.034	63.0	0.60	0.010	62.3	0.10	0.002
C	77.9	79.8	1.90	0.024	76.8	1.10	0.014	77.6	0.30	0.004	77.4	0.50	0.006
D	76.8	78.3	1.50	0.020	77.8	1.00	0.013	77.2	0.40	0.005	75.7	1.10	0.014
E	42.0	44.0	2.00	0.048	43.0	1.00	0.024	43.5	1.50	0.036	41.6	0.40	0.010
F	103.2	103.4	0.20	0.002	105.4	2.20	0.021	103.0	0.20	0.002	102.9	0.30	0.003
G	135.0	135.1	0.10	0.001	136.8	1.80	0.013	134.5	0.50	0.004	134.3	0.70	0.005
H	242.5	244.3	1.80	0.007	244.3	1.80	0.007	247.0	4.50	0.019	242.2	0.30	0.001
I	78.0	77.1	0.90	0.012	77.8	0.20	0.003	77.0	1.00	0.013	77.0	1.00	0.013
J	20.0	18.5	1.50	0.075	19.4	0.60	0.030	19.0	1.00	0.050	20.0	0.00	0.000
Mean	—	—	1.47	0.026	—	1.26	0.017	—	1.19	0.016	—	0.44	0.005
Accuracy	—	—	—	1:39	—	—	1:59	—	—	1:63	—	—	1:200

process were generally adequate. Our analysis showed that our average accuracy level was much greater than the suggested minimum acceptable level. As shown in **Table 1**, the error ranged from undetectable at the width between the desk and back drawers to 1:36 (2.75%) at the width of the entrance.

Comparison of Cameras/Settings

Table 2 shows that one camera is not always consistently better than another. For example, for A, deviation of the Canon G1 is almost four times that of the disposable camera, whereas for B **(Figure 7)**, it is only one-seventh as much. This variation in relative deviation exists because 3-D reconstruction from 2-D photographs depends mainly on manual marking and referencing tasks in the software. Therefore deviations can occur within a tolerable range, just as random deviations occur in the tape measurement of real space.

Although the model generated with pictures from the disposable camera was less accurate than models generated with pictures from the digital cameras, its accuracy was within the tolerable range. The accuracy of the model generated with pictures from the low-resolution digital camera also compared well with the model from the high-resolution digital camera pictures. The highest accuracy was obtained with the high-resolution digital camera with the wide-angle lens; perhaps the larger field of view enabled better images for generating the model. The person performing the modeling noted that images from the high-resolution Canon G1 camera were easier to use in the modeling procedure and therefore required less time to process than did images from the disposable or

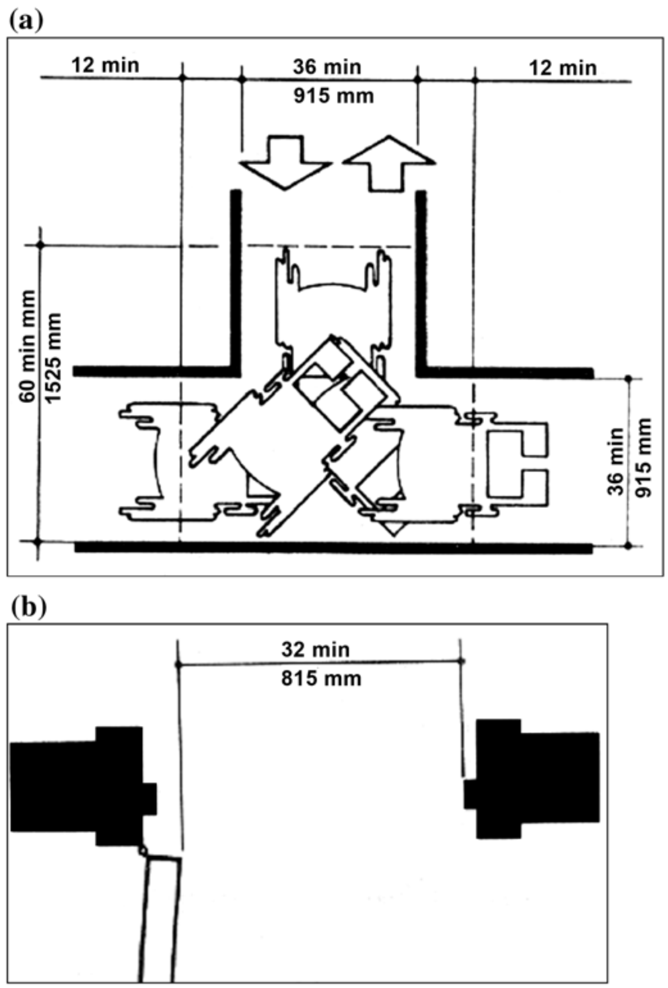

Figure 10.
Americans with Disabilities Act Accessibility Guidelines for **(a)** wheelchair turning space: T-shaped space for 180° turns and **(b)** clear doorway width and depth detail (min = minimum). Measurements given in inches, unless otherwise noted.

low-resolution cameras. Although the disposable camera produced less accurate models than did the other camera configurations, its models are likely sufficiently accurate for assessing wheelchair accessibility. That is, its average deviation level was within the suggested tolerable accuracy level, 1:30. Moreover, the disposable camera has the advantages of affordability and ease of use.

We can see that the higher the resolution and function of the camera, the higher the accuracy of the 3-D models (**Table 2**). We can see, too, the decrease in labor hours to construct 3-D models for the second experiment (**Table 3**). On the other hand, the high-end camera is less affordable and more difficult to use because of its complicated functions. However, because the technology has progressed, the current consumer-grade digital camera is of higher resolution than the high-end digital camera of 3 years ago. For example, while a high-performance G-series digital camera by Canon has advanced from the Canon G1 with 3.3 megapixel resolution to the Canon G6 with 8 megapixel resolution, a consumer-grade A-series camera by Canon has evolved from 1.3 megapixel (Canon A1) to 4 megapixel (Canon A95) resolution. The built environment might be difficult to reach and for a professional to return to repeat the photography would be expensive. Thus, taking many photographs of the object or area being measured is a good idea. A larger memory capacity allows the photographer to shoot a larger number of photographs from slightly different angles in a short time and thus increases the chance of producing good photographs for 3-D models. The consumer-grade digital camera has become more advantageous in both usability and accuracy as compared with other cameras/settings. We decided to use the consumer-grade digital camera for our further studies.

Feasibility Test

Accessibility assessment via the virtualized environment was similar to the on-site assessment by an experienced rehabilitation engineer. That is, a rehabilitation engineer obtained similar measurements and could confirm that findings from the 3-D models were correct. We can see the measurements and findings from the two methods in reference to wheelchair dimension and ADAAGs in **Table 4**. The dimensions of the wheelchair in this experiment were 27 in. (width) by 44 in. (length) by 27.5 in. (height to knee).

Because this is a pilot study for further comprehensive field trials, we only performed the assessment to test the applicability of the software and hardware with a simple procedure. We are developing a comprehensive and systemic evaluation form so that the architect or rehabilitation engineer can assess the accessibility objectively. As shown in the example checklist of tasks for the evaluation of accessibility in **Figure 11**, we broke down activities into task components that can be more readily understood in terms of functional capabilities. We referred to the CASPAR™ to develop checklist items. In addition to the tasks of the CASPAR™, we added some features necessary for wheelchair users, such as whether enough space exists to build a ramp or install a stair glide or lift. Besides taking dimension measurements, we

Table 3.
Number of photographs and labor hours required to construct three-dimensional models for three experiments.

Experiment	Space	Camera	Photographer	Photographs Taken	Photographs Used	Labor Hours
Accuracy Analysis	Office	Canon G1	Investigator	91	5	7.5
Camera Comparison	Bathroom	Disposable	Investigator	14	7	4.5
		Canon A10		18	7	3.5
		Canon G1		17	7	3.0
		Canon G1 wide-angle lens		12	6	2.5
Feasibility Analysis	Living Room	Canon A10	Wheelchair user's friend	15	9	4.0
	Bedroom			7	4	1.5
	Entrance			11	6	2.0
	Bathroom			13	7	2.5

Table 4.
Assessment results of feasibility test. Comparison between on-site measurements, 3-dimensional (3-D) model measurements, dimensions of wheelchair and Americans with Disabilities Act Accessibility Guidelines (ADAAGs). Findings are from 3-D model assessment and all were confirmed by on-site measurements.

Space	Measurement	3-D Model (in.)	On-Site (in.)	Wheelchair Dimension (in.)	ADAAG (in.)	Finding
Bedroom	Doorway clearance	27.8	27.8	Width 27.0	32.0	Doorway narrow
	Space around bed	36.7	37.5	Width 27.0	36.0	Bed accessible
Bathroom	Height of shower threshold	4.4	5.5	—	0.0	Threshold should be removed
	Lavatory clearance	30.7	30.5	Height 27.5	29.0	Lavatory accessible
	Doorway clearance	34.4	33.5	Width 27.0	32.0	Doorway accessible
Entry	Wheelchair turning space	46.6	47.5	Length 44.0	36.0	Wheelchair turning space adequate
	Entrance doorway clearance	34.6	33.7	Width 27.0	32.0	Entrance accessible
Living Room	Entrance clearance	34.4	35.0	Width 27.0	32.0	Entry doorway accessible
	Kitchen doorway clearance	27.0	27.5	Width 27.0	32.0	Kitchen doorway narrow
	Dining table clearance	28.4	29.0	Height 27.5	27.0	Dining table accessible

could assess the physical environment more comprehensively and objectively by checking what tasks are problematic in a given space.

To assess the accessibility of the wheelchair users' built environment, we need preliminary information about their medical diagnosis, mobility aids, and home environment, especially what they want and need for home modifications beyond the dimension measurements. As shown in the sample survey form in **Figure 12**, the structure will be broken into several areas and each area will be detailed by occupational tasks that the user might have difficulties performing. We can get users' opinions from this survey before measuring and evaluating the target environment.

As we can see in **Table 3**, the feasibility analysis shows remarkable improvement in labor hours and number of photographs required for constructing 3-D models over the first. The wheelchair user's friend had no previous familiarity with this 3-D modeling concept and was educated through our guidelines. The investigator now could construct 3-D models within acceptable labor hours with the photographs taken by the wheelchair

Entrances to Home
Location: ________ Type: ________

☐ Enough space to build ramp
Specify modification: ____________

☐ Enough space to install stair glide
Specify modification: ____________

☐ Enough space to install lift or elevator
Specify modification: ____________

☐ Enough space to reach entrance from street, driveway, or sidewalk
Specify modification: ____________

☐ Enough space to maneuver at entry door
Specify modification: ____________

☐ Enough space to go through entry door
Specify modification: ____________

☐ Enough space to go up and down stairs
Specify modification: ____________

☐ Enough space to lock and unlock entry door
Specify modification: ____________

☐ Enough space to open and close entry door
Specify modification: ____________

☐ Enough space to go over threshold at entry door
Specify modification: ____________

☐ Other (Specify):
Specify modification: ____________

Figure 11.
Checklist for accessibility assessment of wheelchair user's home entrances.

Problems

Check the box labeled **problem**, if the task is a problem for the client to do alone or if the task cannot be done.

☐ Getting to any entrance from the street, driveway or sidewalk.

☐ Maneuvering any entry door.

☐ Going through any entry door.

☐ Going up and down stairs to any entry door.

☐ Locking or unlocking any entry door.

☐ Opening or closing any entry door.

☐ Going over the threshold at any entry door.

☐ Other (specify): ____________

List the type of mobility aid(s) and assistive **devices** used in completing the task.

Device: ____________

Figure 12.
Survey form for preliminary information.

user's friend. This improvement can be attributed to two factors: one is the learned skill of the investigator; he got used to handling the program. Another is that the guidelines for taking appropriate photographs have been set. Although a learning effect of the investigator for handling the software program could exist, we can conclude that the guidelines also are effective for educating a naïve photographer on how to take appropriate pictures for constructing 3-D models of interior physical environments. However, we need to conduct a randomized controlled trial to validate the reliability of our developed guidelines.

To analyze and compare costs of the two methods, we assumed a typical case, which has four architectural parts and requires 3 hours travel time by car. We estimated 1.5 hours for constructing the 3-D model of part of a home based on the results of the feasibility test and on our experience thereafter. We computed labor hours for the conventional on-site (COS) method based on billing methods of the architect firm, Lynch & Associates (Pittsburgh, Pennsylvania). The rates per hour of personnel were adapted from estimates by the Center for Assistive Technology (Pittsburgh, Pennsylvania) and Lynch & Associates. **Table 5** shows the costs related to personnel labor hours of for each method.

Though technician labor hours and travel distance to a user's built environment will vary in each case, this cost analysis shows potential benefits of the RAAS over the COS method. For the architect, we anticipate remarkable cost advantages of the RAAS over the COS method. For the rehabilitation engineer, we anticipate little difference in cost between the two methods, but we can still value the critical advantage of the RAAS because availability of service delivery is more important than cost-effectiveness for disabled persons in underserved areas. In particular, we can see that the farther the geographical distance, the greater the benefits of the RAAS method.

Limitations

Although we demonstrated the potential value of the RAAS through three experiments, the method has some limitations. First, even with developed guidelines, for a novice to take appropriate 2-D pictures for the 3-D reconstruction of an interior built environment is still a challenge. Second, the RAAS cannot provide sufficient and effective communication between the user and the

Table 5.
Analysis of potential cost for different methods of accessibility assessment.

Method	Personnel	Labor Hours	Rate per Hour	Cost
Remote Accessibility Assessment System				
Travel	Student	6	$10.00	$60.00
Photography	Student	2	$10.00	$20.00
3-D Reconstruction	Technician	6	$50.00	$300.00
Total	—	—	—	$380.00
On-Site (Architect)				
Travel	Architect, Assistant	6	$100.00, $50.00	$600.00, $300.00
Investigation	Architect, Assistant	1	$100.00, $50.00	$100.00, $50.00
Measurement	Architect, Assistant	2	$100.00, $50.00	$200.00, $100.00
Total	—	—	—	$1,350.00
On-Site (Rehabilitation Engineer)				
Travel	Rehabilitation Engineer	6	$50.00	$300.00
Investigation	Rehabilitation Engineer	1	$50.00	$50.00
Measurement	Rehabilitation Engineer	2	$50.00	$100.00
Total	—	—	—	$450.00

service provider. To overcome this limitation, we are developing a videoconferencing and teleimaging system through which the user can videoconference with the specialist while photographing the environment. Using this system, the provider will guide the user through the process and thereby ensure the inclusion of all the important features of the environment. Third, learning to construct 3-D models with photogrammetry software remains a time-consuming job. However, as technologies evolve, becoming easier to use and available at lower cost, we can consider the possibility of automatic 3-D reconstruction technologies that use a video camera or laser scanner. Finally, we could not conduct the architect's evaluation via the COS method because the architect's fee was too high for the feasibility analysis of a pilot study. This study will be followed by the development of enhanced algorithms and several new instruments: a survey form, a measurement form, and an evaluation form. We will design and perform a comprehensive field evaluation with more data to assess the value of the RAAS compared with the COS method. We will then be able to calculate the degree of agreement in accessibility assessments between the two methods and analyze their cost-effectiveness with real data.

CONCLUSION

We determined that PhotoModeler was capable of producing sufficiently accurate 3-D models for the assessment of the accessibility of a wheelchair user's home. Through the comparison of cameras/settings systems, we concluded that a disposable camera or a consumer-grade digital camera can be used in the RAAS. Finally, the field feasibility test of the hardware and software instruments, adapted through a first and second analysis, showed these instruments to be appropriate. Based on the results of the above reliability analyses, we concluded that the VR assessment with the Canon A10 digital camera and PhotoModeler software would be an appropriate and useful intervention tool for accessibility assessment of a wheelchair user's home environment. If we are successful in developing a RAAS for analyzing accessibility of the physical environment, the system could improve rehabilitation outcomes by making accessibility assessments and modifications available to a larger proportion of the population of disabled persons.

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