가상현실기술을 이용한 원격휠체어접근성평가시스템의 개발

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Development of a Remote Wheelchair Accessibility Assessment System Using Virtualized Reality Technology

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Abstract

Home modification has come to be recognized as an important intervention strategy to manage health care conditions, maintain or improve functioning, ensure safety, and reduce the wheelchair user's dependency on others. However, the availability of skilled professionals with experience in home modifications for accessibility is limited. A system that enables accurate remote assessments would be an important tool to improve our ability to perform home assessments more easily and at decreased cost.

A Remote Wheelchair Accessibility Assessment System (RWAAS) using Virtualized Reality(VR) technology was developed that enabled clinicians to assess the wheelchair accessibility of users' built environments from a remote location. Characteristics of the camera and 3D reconstruction program chosen for the system significantly affect its overall reliability. In this study, we performed two reliability analyses on the hardware and software components: 1) Verification that commercial software can construct sufficiently accurate 3D models by analyzing the accuracy of dimensional measurements in a virtualized environment; 2) comparison of dimensional measurements with four camera settings. Based on these two analyses, we were able to specify a consumer level digital camera and the Photomodeler Pro software for this system. And we then tested the feasibility of the selected software and hardware in an actual environment.

Lastly, A field evaluation was performed to test whether this new system is comparable to the traditional method of accessibility assessment to evaluate its ability to assess the accessibility of a wheelchair user's typical built environment. The results of field trials showed high congruence between the assessments by two methods. Findings suggested that the RWAAS assessments have the potential to enable specialists to assess potential accessibility problems in built environments regardless of the location of the client, home, or specialist.

Key words: 3D Reconstruction, 3D model, Accessibility, Camera, Home Modification, Telerehabilitation, Virtual Reality, Wheelchair

1. Introduction

According to the Census Bureau's Survey of Income and Program Participation, the number of wheelchair users aged 18 years and over in 1999 was estimated at more than 2.3 million in the U.S. [1] An important trend in usage of wheeled mobility devices is that the number of people using wheelchairs is increasing yearly; thus the demand for wheelchairs is likely to continue to grow in the foreseeable future [2].

For any given limitation in function, the amount of disability an individual experiences will depend on the quality of the social and physical environment [3]. Most importantly, for mobility devices to be used effectively, the environments in which they are used must be physically accessible [4].

Effective home modification requires consultation with skilled professionals capable of assessing the home environment and identifying changes necessary to meet the wheelchair user's needs. While there are many building and remodeling contractors able to perform the modifications, the availability of skilled professionals with experience in home modifications for accessibility is limited [5]. Providing services in rural areas is particularly difficult. Such service requires lengthy travel times that increase cost and consume the limited time of skilled professionals. Even if a specialist is willing to travel a long distance, travel cost is too high relative to the fee for modification. And even a specialist couldn't accurately assess the environment's accessibility without visiting the site.

A system that enables accurate remote assessments would be an important tool to improve our ability to perform home assessments more easily and at decreased cost. Therefore, this study addressed the development of a remote accessibility assessment system using the concept of telerehabilitation and the virtual reality technologies and the evaluation of their effects [6]. This system used commercial software to construct 3D virtualized environments from photographs. Custom screening algorithms and instruments for analyzing accessibility have been developed.

In this study, a new and alternative solution was developed—the Remote Wheelchair Accessibility Assessment System (RWAAS) which uses accessibility screening algorithms to evaluate wheelchair accessibility of an individual's physical environment, taking advantage of state-of-the-art technologies of digital imaging, 3D reconstruction, and photogrammetry. The study includes the development of algorithms that will standardize and simplify procedures for assessing the accessibility of the home environment, using the above technologies. Our solution includes the development of several new tools, such as a guidelines book on how to take photos, a survey form, a measurement form, and an evaluation form. The study has developed a comprehensive procedure for assessment of the home environment's accessibility, using telerehabilitation and virtual reality technology. The study explored the most effective means of constructing 3D models from 2D photos of an interior architectural environment, including how to take efficient photos and how to effectively manipulate the commercial software.

Finally, we evaluated our newly developed method by examining agreement between the RWAAS method and the Conventional In Person (CIP) method for assessing the accessibility of a wheelchair user's home.

2. Pilot Studies

2-1. Accuracy Analysis

The RWAAS requires 3D reconstruction of the physical environment. We can turn to laser scanning technologies as a fast way to acquire accurate measurements of built environments. Although active methods such as range finding or laser scanning are accurate, they require specially trained operators [7] they are still too expensive for practical application to individual's homes. [8]. Therefore, this study will use photogrammetry technology that constructs 3D models from 2D images, to acquire 3 dimensional views Among several photogrammetry software on the market, Photomodeler has more scientific applications and shows evidence of high accuracy relative to other ones such as Imagemodeler and Viewpoint. Therefore we chose Photomodeler Pro 4.0 for use in the RWAAS for the following reasons: accuracy is the most important factor in 3D reconstruction; its 3D reconstruction features best fit the requirements of our system; it provides many easy-to-use tools; and several studies support its value.

A work by NASA [9]and several other works [10, 11, 12] showed that Photomodeler Pro has a high precision enough to make 3D models. However, NASA's and Fedak's applications used the software to model the exterior of objects, which differs significantly from our interior environment modeling application. We therefore evaluated its ability to produce a sufficiently accurate 3D model for our application by analyzing the accuracy of dimensional measurements in the virtualized environment of a wheelchair user's office space [13].

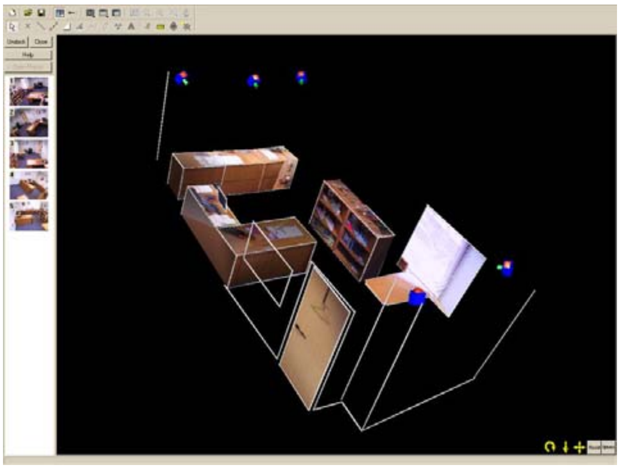

Figure 1. A reconstructed 3D model of an office room

This trial showed an average precision value of 200:1 (0.51%) (Table1). This degree of precision could result in a measurement error of 4 mm (0.16″) for a typical 800 mm (32″) door opening. An experienced architect on our research team suggested that the precision value of 30:1 is tolerable accuracy for assessing wheelchair accessibility. Sanford et al produced a similar tolerance level in their study [14].

They stated that because all measurements would be field verified by a contractor prior to construction, measurements within approximately an inch during the assessment process were generally adequate. Our analysis showed that our studies' average precision level was much more accurate 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 36:1(2.75%) at the width of the entrance.

2-2. Comparison of Camera Systems

Usability was a primary consideration for the RWAAS design. Because the proposed technique of 3D reconstruction is based on object image acquisition, techniques and logistics involved in acquiring images are critically important [15]. To study the tradeoff between the usability and accuracy, we compared the modeling accuracies of four different cameras/camera settings including a disposable camera and three digital camera variations [13, 16]: a disposable camera (Giant Eagle, disposable film camera with 1.5 mega pixel photo CD scan); an inexpensive consumer level digital camera (Canon A10, 1.2 mega pixel); a high resolution digital camera (Canon G1, 3.3 mega pixel); and a high resolution digital camera with a wide angle lens (Canon G1, 3.3 mega pixel with Canon Wide Converter WC-DC58, 0.8 x wide). Images from each camera were used to assess the bathroom of a wheelchair user's house.

We can see that the higher the resolution and function of the camera, the higher the accuracy of the 3D models (Table 2). On the other hand, the high-end camera is less affordable and more difficult to use for its complicated functions. However, as the technology progresses rapidly, the current consumer level digital camera achieves higher resolution than does a high-end digital camera of three years ago. The larger memory capacity allows the photographer to shoot a vast number of photos from slightly different angles in a short time,

	Real measurement	Calculated measurement	Deviation	Deviation ratio	Shared photos
• desk depth	76.0	76.0	Base scale		5
A) desk width	167.5	167.4	0.1	0.06%	4
B) desk height	73.5	73.2	0.3	0.41%	2
C) side desk width	122.0	121.1	0.9	0.74%	2
D) side way	96.0	95.9	0.1	0.10%	3
E) back way	180.5	180.5	0.0	0.00%	2
F) entrance	91.1	93.6	2.5	2.74%	2
Mean	121.8	--------	0.7	0.51%	2.5

Table 1. Measurement Precision in centimeters of 6 targets in a room

(unit : cm)

Object	Tape	Disposable Camera			Canon A10 Camera			Canon G1 Camera			G1 Wide Lens		
	Measure	Measure	DEV	Ratio	Measure	DEV	Ratio	Measure	DEV	Ratio	Measure	DEV	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
Ave.			1.47	0.026		1.26	0.017		1.19	0.016		0.44	0.005
Precision				39:1			59:1			63:1			200:1

Table 2. Measurements from 5 different environments of the target bathroom

thus increasing the chance of providing good photos for constructing 3D models. Now, the consumer level camera has become more advantageous in terms of both usability and accuracy as compared with other camera settings.

2-3. Feasibility test

After performing two reliability analyses on the hardware and software components, we applied these instruments to an actual built environment of a wheelchair user to demonstrate their ability to assess the accessibility of a wheelchair user's typical built environment. This feasibility test was conducted using the Canon Powershot A10 digital camera with 1.2 mega pixel resolution. The target environment was a client's apartment unit where one of the occupants uses a standard powered wheelchair [13, 17]. One wheelchair user's friend was instructed how to take the photographs using the guideline book. He took about 60 pictures, 15 pictures each per four subparts of the apartment: entrance hall way, bedroom, living room, and bathroom.

Using the 3D models constructed with the Photomodeler Pro from 2D photos obtained by the Canon A10 digital camera, the investigator discovered that the kitchen doorway and bedroom doorway should be widened and the curb of the shower booth removed, but that the bathroom door, entrance door, dining table, and lavatory could accommodate the user's wheelchair. T-shape turning space of the entry also was accessible according to the ADA Accessibility Guideline (ADAAG) (Figure 2) and the client's wheelchair dimension 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 by 3D models were correct.

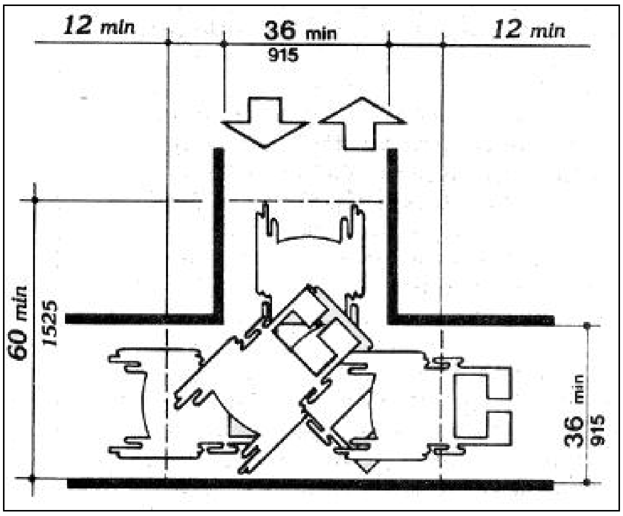

Figure 2. Shaped Space for 180 Degree Turns (ADAAG)

3. Field Trials

Based on results of the above reliability analyses, we concluded that the virtual reality assessment using the A10 digital camera and Photomodeler Pro would be an appropriate and useful intervention tool for accessibility assessment of a wheelchair user's home environment. And we then performed the field evaluation of the developed system in order to evaluate the VRTS as compared to the conventional method [18].

3-1. Methods

Three home environments were recruited in this study. Participants in this study were the owners or occupants of a home who were also clients of an architecture firm specializing in universal design. For each home environment, three cases from three imaginary subjects were evaluated. In each evaluation case of an imaginary subject and a home environment, approximately 70 tasks were assessed.

For each home environment, the architecture firm investigated the physical environment by visiting their client's house, and for each situation of the three imaginary subjects, the architect from the firm evaluated accessibility of the target home via his own conventional method. For the VRTS method, the owner/occupant's home was photographed by a student assistant, and 3D models of the home environment were constructed from the 2D photos by a technician. Another architect then evaluated accessibility via the VRTS in the virtualized environment of the target home for each case of the three imaginary subjects.

Both evaluators assessed a number of tasks (usually about 70) in a home evaluation by using the same evaluation form. Evaluators were blinded to each other's assessment. The assessment addresses several problem areas of the home, and each area has a number of associated tasks. Each task was designated as problematic or not, hence, in need of modification or not, by each architect evaluator. The evaluation results of all tasks were dichotomous data that indicated whether or not specific tasks were problematic.

3-2. Procedure

A) Recruitment

If an individual requested a home accessibility assessment through the architecture firm Lynch & Associates, the architect then instructed any interested customer to contact the investigator. Customers who were interested in the study were contacted by the investigator via telephone and consent form was obtained via mail.

B) Creating Imaginary Subjects

Instead of actual clients, three imaginary situations were created through completion of the survey form for three imaginary subjects. This survey form was filled out by the investigator in the name of each of three imaginary subjects per each house. Nine surveys were completed for each of three imaginary clients in each of three homes.

C) Acquisition of Images

Pictures were then taken of the client's home environment. In this study, three students of the school were recruited as part-time assistants for the image acquisition. When he/she took pictures of a problem area, at least two carpenter's squares were located in the middle of the space. And he/she sketched a rough floor plan of the home environment which showed where each problem area was located.

D) Evaluation via the CIP

The architecture firm of Lynch and Associates conducted the Conventional In-Person assessment by visiting their client's home and investigating the physical environment. The architect completed the evaluation form with the information from the on-site investigation and measurement of his/her client's home environment.

E) 3D Modeling

A 3D model was made for each problem area, using the 3D modeling software, Photomodeler Pro. Once the model was constructed, the technician measured the dimensions of norm objects (carpenter's squares) in the 3D model in order to determine whether the model was accurate enough to be used for the accessibility assessment.

F) Evaluation via the RWAAS

Another architect from Tusick and Associates then evaluated the accessibility and assessed the modification requirements for each imaginary client's situation, using the virtualized model of each home environment, and referring to 2D photos and preliminary information from

Category	True Response		Kappa k(p-value)	Odds Ratio [95%CI]	McNemar (p-value)
	True Positive: Sensitivity	True Negative: Specificity			
Total	94.1%(576/612)		.857(.000)	205.272 [104.062, 404.921]	(.868)
	95.6%(417/436)	90.3%(159/176)			

Table 3. Agreement Rates for Overall Observation

the survey form. She also used the evaluation form to evaluate all tasks in all problem areas in an orderly and systematic way.

G) Comparing Two Methods

The investigator compared the data from each evaluation form, completed by the two architect evaluators, to determine the level of agreement between the evaluation results via the VRTS method and the CIP method.

3-3. Results

We used the Conventional In-Person assessment as the baseline to compare the VRTS protocol. The proportion of overall agreement was highly observed as 94.1% and the overall sensitivity and specificity was reported as 95.6% and 90.3% respectively. As a significant Kappa coefficient of .857 and the 95% Confidence Interval of Odds rate of [104.062, 404.921] were calculated, a high level of overall agreement rate was shown. And high p-value (.868) of the McNamar test implied that there was no marginal homogeneity, that is, no tendency to identify the task incorrectly in the positive or negative direction.

4. Summary and Conclusion

The results of field trials showed high congruence between the assessments by two methods. Findings suggested that the VRTS assessments have the potential to enable specialists to assess potential accessibility problems in built environments regardless of the location of the client, home, or specialist. This study also provided the evidence that a virtual reality telerehabilitation system can be an alternative, cost-effective solution to conventional rehabilitation services. The data from this study compare favorably with the results previously reported for the Comprehensive Assessment Survey Protocol for Aging Residents (CASPAR) [19], a remote, paper and pencil assessment protocol and the telerehabilitation system using the telephone line based videoconferencing system [14]. The RWAAS provides specialists with three-dimensional views of the physical environment and photos oriented with a 3D model, which gives specialists the opportunity to better figure out the environment and to more easily measure the physical 3D dimension. These features might contribute to the improved performance of this study. We will improve the system continuously with the state-of-the-science technologies and this progress in this study will provide a means of accessibility assessment for wheelchair users in underserved areas who otherwise would not have access to evaluations of their built environments by professionals. The VRTS can be utilized in both homes and public spaces, and the study shows the potential for applications of virtual reality technology in the area of architectural interior environment, such as in the interior design and home renovation industries.

5. References

1. McNeil, J M. Americans With Disabilities: 1997 U.S. Department of Commerce, Economics and Statistics Administration, Bureau of the Census 2001.
2. Brandt E Jr. and Pope A (eds.). Enabling America. *National Academy Press* 1997.
3. U.S. Department of Housing and Urban Development and U.S. Census Bureau, American Housing Survey for the United States, Supplement: 1995, Current Housing Reports, Series H151/95, U.S. Government Printing Office, Washington, D.C., forthcoming.

4. LaPlante LM. Demographics of Wheeled Mobility Device Users, Requirements for Wheeled Mobility: An International Workshop, 2002. Http://www.ap.buffalo.edu/idea/space%20workshop/

5. Extended Home Living Services, Comprehensive Assessment and Solution Process for Aging Residents. (http://www.ehls.com/caspar/caspar.html), 2002.

6. Cooper RA, Ding D, Simpson R, Fitzgerald SG, Spaeth DM, Guo S, Kuntz AM, Cooper R, Kim J, Boninger ML, Virtual Reality and Computer-Enhanced Training Applied to Wheeled Mobility: An Overview of Work in Pittsburgh, *Assistive Technology* 2005; 17(2). 159-170

7. Leica Geosystems HDS, Leica Geosystems HDS LLC. http://hds.leica-geosystems.com/index.html

8. Laiserinm J. High Tech for Old House. *Old House Journal* Oct 2001 http://www.oldhousejournal.com/magazine/2001/sep_oct/high_tech.shtml

9. Pappa RS, Giersch LR, Quagliaroli JM. Accuracy Study on Photogrammetry of a 5m Inflatable Space Antenna With Consumer Digital Cameras http://www.photomodeler.com/pdf/NASA.pdf

10. Lynnerup N. Andersen M. Lauritsen HP. Facial image identification using Photomodeler. *Legal Medicine* Sept., 2003: 5(3):156-60.

11. Vedel J. Developing 3D Models from Photos. *Architecture Week* Jan, 2002; T1:1 – 23 http://www.architectureweek.com/2002/0123/tools_1-1.html

12. Fedak M, 3D Measurement Accuracy of a Consumer-Grade Digital Camera and Retro-Reflective Survey Targets http://www.photomodeler.com/pdf/fedak1.pdf

13. Kim J. Brienza DM. Development of a Virtual Reality Telerehabilitation System for Analyzing Accessibility of the Built Environment, *Journal of Rehabilitation Research and Development* 2005, 9 Accepted

14. Sanford JA, Jones M, Daviou P, Grogg K, Butterfield T. Using Telerehabilitation to Identify Home Modification Needs, *Assistive Technology* 2004; 16(1).

15. Knyaz VA, Yu S. Zheltov. Vision based technique for photorealistic 3D reconstruction of historical items http://www.gisdevelopment.net/application/archaeology/general/archg0014.htm

16. Kim J. Brienza DM. The Virtual Reality Telerehabilitation System for Analyzing Accessibility of the Physical Environment: A Comparison of Camera Systems; Proceeding of RESNA 26th International Conference, June 2003

17. Kim J. Brienza DM. The Virtual Reality Telerehabilitation System for Analyzing Accessibility of the Physical Environment: A Feasibility Test ; *Proceeding of RESNA 28th International Conference,* 2005

18. Kim J. Development and Effectiveness Evaluation of a Virtualized Reality Telerehabilitation System for Accessibility Analysis of Built Environment, *PhD Dissertation*, University of Pittsburgh, http://etd.library.pitt.edu/ETD/available/etd-09152005-153646/unrestricted/KimJongBae_etd2005.pdf

19. Sanford JA, Pynoos J,, Tejral A,, Brown A.. Development of comprehensive assessment for delivery of home modifications. *Physical and Occupational Therapy in Geriatrics* 2002; 20(2): 43-55.