Spatial data acquisition, integration, and modeling for real-time project life-cycle applications

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Summary

Current methods for site modeling employs expensive laser range scanners that produce dense point clouds which require hours or days of post-processing to arrive at a finished model. While these methods produce very detailed models of the scanned scene, useful for obtaining as-built drawings of existing structures, the associated computational time burden precludes the methods from being used onsite for real-time decision-making. Moreover, in many project life-cycle applications, detailed models of objects are not needed. Results of earlier research conducted by the authors demonstrated novel, highly economical methods that reduce data acquisition time and the need for computationally intensive processing. These methods enable complete local area modeling in the order of a minute, and with sufficient accuracy for applications such as advanced equipment control, simple as-built site modeling, and real-time safety monitoring for construction equipment.

This paper describes a research project that is investigating novel ways of acquiring, integrating, modeling, and analyzing project site spatial data that do not rely on dense, expensive laser scanning technology and that enable scalability and robustness for real-time, field deployment. Algorithms and methods for modeling objects of simple geometric shape (geometric primitives from a limited number of range points, as well as methods provide a foundation for further development required to address more complex site situations, especially if dynamic site information (motion of personnel and equipment). Field experiments are being conducted to establish performance parameters and validation for the proposed methods and models. Initial experimental work has demonstrated the feasibility of this approach.

1. Introduction

The dynamic nature of the construction environment requires not only that a real-time local-area modeling system be fast but also that it be capable of dealing with uncertainty and adjusting to changes in the work environment. The ability to cope with uncertainty is very important and is being recognized as the next logical step in the robotics field as well.

Currently, 3D laser-scanning system and photogrammetry are used to create world models of construction sites. 3D laser-scanning system is very accurate, but it is time consuming and a lot of resources are needed to create construction-site scenes. A detailed and highly accurate model is not always necessary in applications, however; in many situations, a set of simple, primitive shapes can be used in its place. One of the most prominent 3D laser-scanning systems to date is known as LADAR (for Laser Distance and Ranging), which is being utilized by the National Institute of Standards and Technology (NIST) for use in applications such as automated earthmoving status determination, 3D as-built modeling of construction sites, and material tracking systems (Stone et al., 2000; Cheok and Stone, 1999). There are, however, certain disadvantages in using 3D lasers, such as their lack of traceability, the high cost and large size of the equipment required for their use, and the length of time needed for the processing phase (Stone and Cheok, 2001).

Photogrammetry is a passive modeling method that entails the acquisition of 3D measurements from images and usually employs a perspective optical sensor (Fabio, 2003). Manual processes, such as film scanning, interior orientation, aerial triangulation, and editing for matching, are required for its use and the use of photogrammetry for data acquisition is greatly dependent on the environmental conditions on the sites where it is used, as it can be done only in the presence of considerable daylight, with virtually no clouds or shadows (Baltsavias, 1999).

There are several institutions at which research on the modeling of industrial scenes is under way. One of these, Sandia National Laboratory, has developed a method for making use of primitives to construct 3D world models (Luck et al., 1998). Geometric primitives are not limited to the representation of industrial scenes, however; they can be ideal for modeling construction environments as well, since they require very little memory, even for large world maps, and they are easy to store and manipulate. Rapid 3D workspace modeling methods that use a sparse range-point cloud achieve an acceptable balance between the degree of human judgment required for their use and the efficiency of acquisition of the range data (Kwon et al., 2003). Such approaches are expected to bring about reductions in both computational costs and processing time—and to lead to cost-effective, robust systems suitable for field deployment and eventual commercialization. While conventional approaches, 3D laser scanning systems, are very precise but slow and require intensive computational capability, methods that incorporate sparse range-point clouds afford a compromise between speed and accuracy of representation of workspaces which is suitable for some real-time field applications.

In many cases, existence of a detailed local model is not critical for the modeling of 3D workspaces. For instance, in applications that entail real-time obstacle avoidance, use of a set of simple polyhedra often suffices.

The aim of the research proposed herein is to develop a 3D spatial modeling method that uses bounding algorithms, including a workspace-partitioning algorithm and an algorithm for constructing a convex hull, and to investigate how well the workspace modeling approach suggested herein succeeds in the representation of construction sites by running experiments in actual construction environments.

2. Process of 3D spatial modeling

A process is to be established for generating 3D spatial models in an efficient manner. The first step of the modeling process is the classification of objects in and around the workspace. In this research, human recognition is employed, since humans are adept at recognizing objects, especially in cluttered scenes such as construction sites (Johnson et al., 1998). This is in contrast to fully autonomous systems (Johnson et al., 1998; Faugeras, 1986; Huttenlocher, 1990), where such human capabilities are not utilized. By incorporating human perception into the overall modeling enterprise, a selected-points-based graphical-modeling approach has the potential to reduce not only the data-acquisition time but also the need for processing that is computationally intensive and/or expensive (Cho et al., 2002). Therefore, integration of the decision-making ability of a human operator with the capability of a robot to carry out certain tasks semi-automatically may be more practical than use of full automation on construction sites (ENR, 1994).

The second step of the modeling process is the acquisition of sparse range-point clouds. Most workspace modeling applications in the construction industry use dense-point-cloud data (e.g. Cyrax, NIST, Carnegie Mellon University). Such processing methods are not only computationally intensive but also time consuming, however, and may render the dense-point-cloud approach prohibitive with respect to real-time applications in the construction industry. The use of sparse point clouds, on the contrary, requires only a very simple process. As mentioned above, that choice is also justified by the use of human recognition systems. Indeed, human recognition skills prove to be a great help in identifying the sparse set of points to be scanned. A flowchart showing the sparse-point-cloud approach developed here for use in rapid 3D spatial modeling is given in Figure 1.

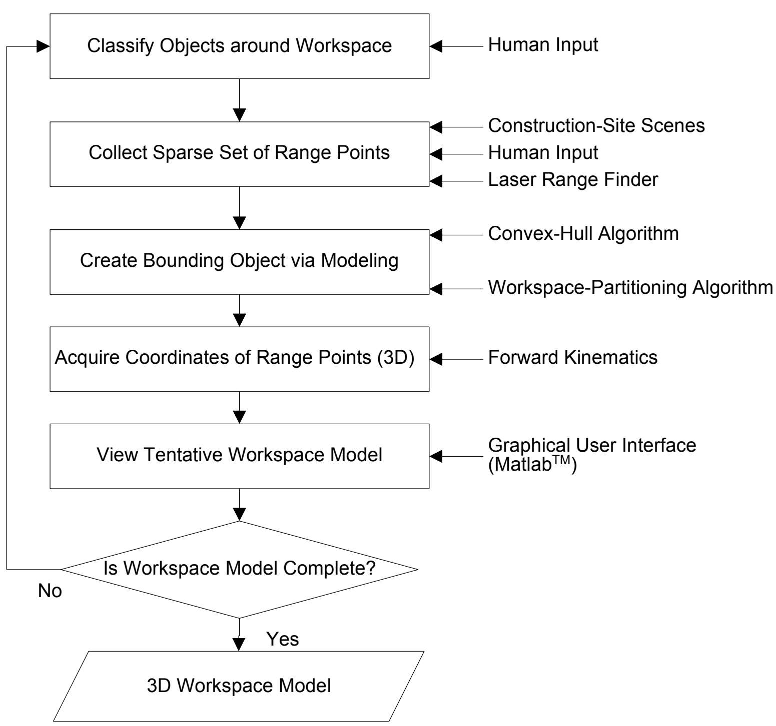

Figure 1 Modeling Process

3. Algorithms of 3D spatial modeling

Convex hulls and workspace partitioning are promising candidates for tools that could be used in modeling construction-site scenes. Convex hulls can be employed in the representation of a wide range of construction-site scenes, such as pipe racks, building structures, and other types of equipment, while workspace partitioning can be used to delimit workspaces. Descriptions of algorithms for both of these tools are given below.

3.1. Convex Hulls

In three-dimensional space, the convex hull of a set of points is the smallest convex volume that contains those points (Barber et al., 1996). There are compelling reasons for using convex hulls for modeling of construction site scene (McLaughlin, 2002):

- Because of their convex nature, such volumes are inherently conservative.
- Any number of points can be picked, anywhere.
- The resulting hull is bounded by planar faces, thereby enabling rapid computation of distances.

The algorithm chosen for use in the research described herein is an incremental algorithm by Barber, Dobkin, and Huhdanpaa which adds just one point at a time to the convex hull generated from the entire set of points processed during earlier steps of the procedure (Barber et al., 1996). The algorithm consists of three parts: initialization, partitioning, and iteration. A detailed description of the workspace-partitioning algorithm is given in the article by Barber et al. An example of the convex-hull modeling process is displayed in Figures 2-5.

Figure 2 Picture of object to be modeled

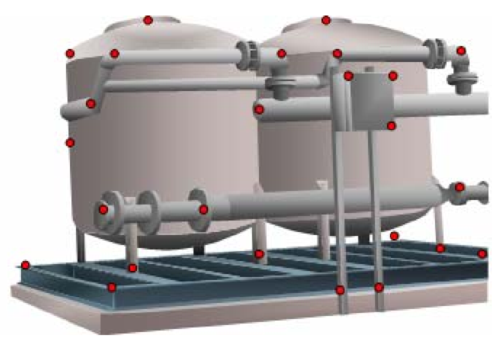

Figure 3 Selected points from laser range finder

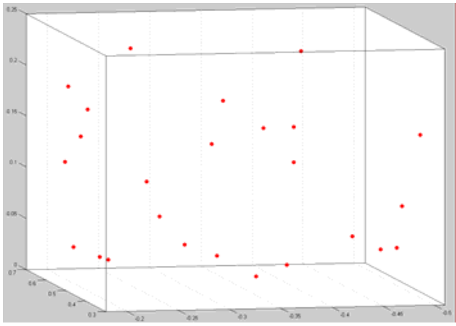

Figure 4 Scanned points

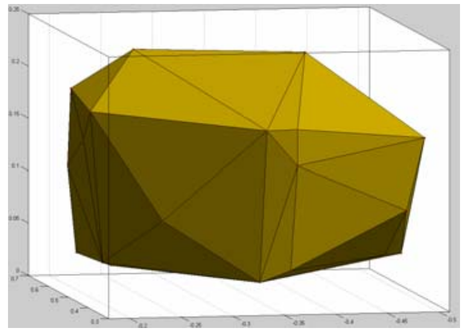

Figure 5 Results of convex-hull algorithm

3.2. Workspace Partitioning

The model to be described is a finite plane (or extremely thin wall) used for partitioning a workspace (McLaughlin, 2002). Geometrically speaking, any set of three non-collinear points suffices to define a plane. However, application of a least-squares approach that uses more than three points, to ensure that the plane is placed where the operator intends it to be, is often a better way to proceed. The simple plane model is very useful for quickly partitioning a scene. Floors, walls, and ceilings can easily be modeled by picking a few additional points. Safety-driven applications can easily be envisaged, such as a backhoe being operated next to a busy city street; in this scenario, a wall would act as a partition between the operator's workspace and the forbidden zone of the street.

In the case of planar regression, the general least-squares problem consists in finding the components (n_x, n_y, n_z) of the vector $\vec{n}$ —the outward-pointing normal to the plane—that minimize the objective function

$$E = \sum_{i=1}^{n} d_i^2 ,$$

where n is the number of range points, d_i is the (signed) distance from range point q_i to the plane, and p is a (fixed) point of the plane. Since

$$d_i = \frac{(\vec{q}_i - \vec{p}) \bullet \vec{n}}{|\vec{n}|},$$

the denominator $|\vec{n}|$ can be eliminated because it merely scales d_i (and contributes only an overall positive multiplicative factor to the objective function). Since p can be any point of the plane, it makes sense to choose p so that $\vec{n}$ is parallel to $\vec{p}$ (with both of them pointing outward, i.e., away from the origin) and $\vec{p} \bullet \vec{n} = 1$, thereby making it easy to locate the resulting plane. On making this choice for p and eliminating the denominator in the formula for d_i, we find that the objective function to be minimized is

$$E' = \sum_{i=1}^{n} \left[\vec{q}_i \bullet \vec{n} - 1 \right]^2 .$$

By taking partial derivatives of E' with respect to n_x, n_y, and n_z, setting each of them to zero, and separating out the coefficients, we get the linear system $A\vec{n} = \vec{b}$, where

$$A = \begin{bmatrix} \sum_{i=1}^{n}(q_{ix})^2 & \sum_{i=1}^{n} q_{ix}q_{iy} & \sum_{i=1}^{n} q_{ix}q_{iz} \\ \sum_{i=1}^{n} q_{ix}q_{iy} & \sum_{i=1}^{n}(q_{iy})^2 & \sum_{i=1}^{n} q_{iy}q_{iz} \\ \sum_{i=1}^{n} q_{ix}q_{iz} & \sum_{i=1}^{n} q_{iy}q_{iz} & \sum_{i=1}^{n}(q_{iz})^2 \end{bmatrix}, \quad \vec{n} = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix}, \quad \vec{b} = \begin{bmatrix} \sum_{i=1}^{n} q_{ix} \\ \sum_{i=1}^{n} q_{iy} \\ \sum_{i=1}^{n} q_{iz} \end{bmatrix},$$

and q_{ix}, q_{iy}, and q_{iz} are the components of $\vec{q}_i$. For the plane determined by the least-squares method, the outward-pointing normal vector $\vec{n}$ is then found by inverting matrix A: $\vec{n} = A^{-1}\vec{b}$. If we want to constrain the plane to be vertical, for instance, as in the case of building a wall, then $n_z = 0$ (assuming that the z-axis points upward) and finding the normal reduces to solving the linear system

$$\begin{bmatrix} \sum_{i=1}^{n}(q_{ix})^2 & \sum_{i=1}^{n} q_{ix}q_{iy} \\ \sum_{i=1}^{n} q_{ix}q_{iy} & \sum_{i=1}^{n}(q_{iy})^2 \end{bmatrix} \begin{bmatrix} n_x \\ n_y \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} q_{ix} \\ \sum_{i=1}^{n} q_{iy} \end{bmatrix}.$$

The extent of the plane can then be determined in any number of ways, such as by projecting each of the $\vec{q}_i$ onto the plane and then finding the maximum horizontal and vertical distance about some prescribed point or relative to the ground. An example of the workspace-partitioning algorithm is shown in Figure 6 through 7.

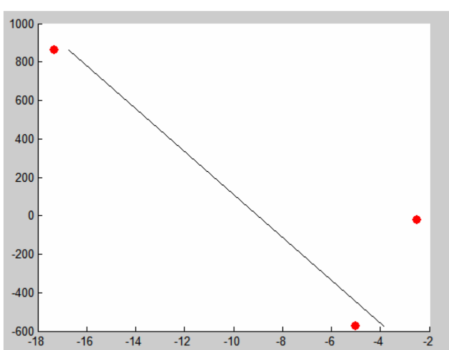

Figure 6. Scanned points and results of least-squares method

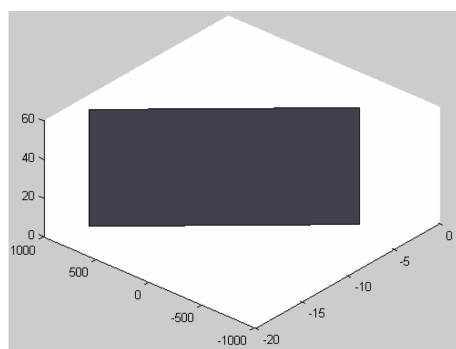

Figure 7. Results of Workspace Partitioning

4. System Description

4.1. Data-Acquisition Setup

In human-assisted modeling, a user interface that is easy to use and understand is important for obtaining good-quality data. The coordinates of range points for various types of objects were acquired in three dimensions by using a laser with pan-and-tilt kinematics and making a transformation from the laser's local coordinate frame to the test-bed world frame. The equipment and software used for data acquisition and modeling consists of 1) a laser range finder, 2) a two-axis pan-and-tilt unit (PTU) controlled by a trackball, 3) a tripod, 4) the laser manufacturer's distance-data-acquisition software, 5) a C program that continuously reads pan and tilt angles from the PTU. The hardware setup is portrayed in Figure 8.

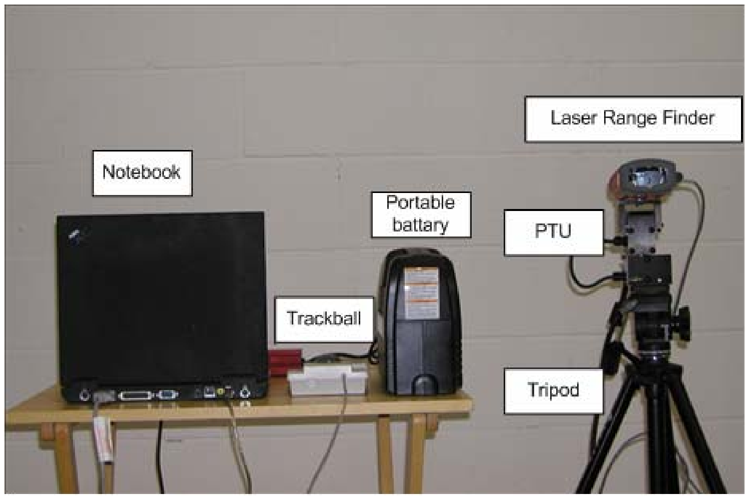

Figure 8 Hardware Setup

4.2. Graphical User Interface for data acquisition

The proposed modeling system requires that the operator run various computer programs (such as the laser manufacturer's distance-data-acquisition software, the pan-and tilt-unit program, and the Matlab graphing program) in order to acquire the range data. For a computer novice, this can be quite challenging; indeed, it is rather cumbersome even for an expert.

In the system proposed herein, a graphical user interface (GUI) enables the equipment operator to acquire data much more readily. The GUI was designed with an option-menu display to enhance the efficiency of data gathering by the operator (Figure 9). Computer command languages offer greater power and flexibility but have an associated high learning cost, while option-menu displays minimize the degree of computer knowledge required of the operator, hence they are easier for novices to learn to use.

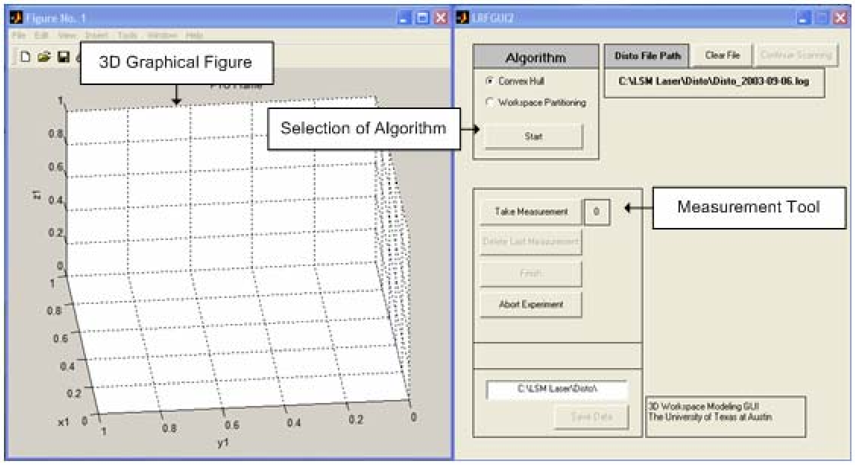

Figure 9 Graphical User Interface

5. Site Experiments

An investigation of how well the workspace-modeling approaches described herein succeed in the representation of construction sites was carried out. The site that was modeled is an urban-building construction site. Photographs of an actual construction site used as a test bed for site modeling are presented in Figure 10. These pictures were taken during construction of the building at Austin. As is often the case in urban construction environments, this construction site is right next to a road that carries heavy traffic, and there are quite a few high-voltage wires strung overhead on utility poles in the immediate vicinity. Furthermore, the workspace zone itself is very narrow, so the workers would most likely be interrupted quite frequently to allow for the movement and operation of heavy equipment on the site. Perhaps of greater concern is the fact that the equipment operator would need to exercise extreme caution because of the presence of high-voltage wires on the construction site.

The National Institute for Occupational Safety and Health (NIOSH) estimates that 15% of electrocutions in the construction industry in the 1980s were the result of inadvertent contact with power lines by cranes or other types of hoisting equipment; this estimate was based on death-certificate data from 1980 through 1989 (NIOSH, 1993). The 3D spatial-modeling process described herein can provide information on the location of such wires in order to delimit the workspace and prevent accidents during the operation of equipment. The purpose of carrying out this graphical-modeling experiment on an urban construction site, using the convex-hull and workspace-partitioning algorithms described earlier, was to demonstrate the potential of the method for enhancing safety on construction sites that are plagued with hazardous conditions.

The model of a boundary to delimit the area where the high-voltage wires are strung overhead on utility poles is presented in Figure 11. A second partition, to divide the workspace from the adjacent road—which sees heavy traffic—is portrayed in Figure 11.

Figure 10 Picture of construction site scene

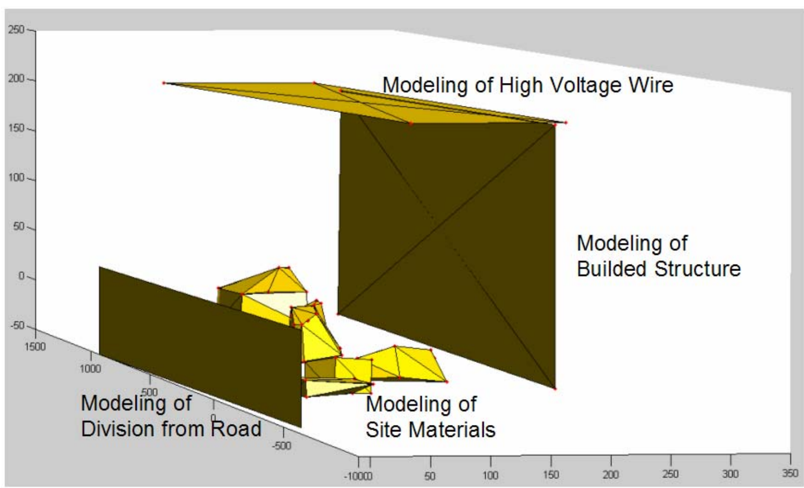

Figure 11 3D Workspace Modeling

6. Conclusion

The proposed spatial-modeling technique using convex hulls and workspace partitioning was devised and tested in actual construction environments. The algorithms used in this approach are computationally efficient and fast enough to be applied to safety enhancement in machine control, and it is also suitable for as-built applications.

The proposed modeling process is suitable for various applications, such as obstacle avoidance (to improve safety) and as-built 3D modeling. Because the process is fast and efficient, it is appropriate for real-time application to equipment operation on a construction site. It may also be used for delimiting workspaces and providing safety zones for workers. The method is not without its limitations, however, especially as regards the representation of dynamic environments on construction sites. (It would be difficult, for example, for this method to represent moving equipment or a worker who is moving from one place to another on the site.)

Nevertheless, it is believed that it could satisfy most of the requirements for 3D modeling. Moreover, flash LADAR could be employed to make up for some of the limitations of the 3D graphical-modeling approach described herein, such as in the representation of moving objects (including people), though it cannot be used for modeling per se. The possibility of using flash LADAR with sparse range-point clouds is being studied.

The modeling method presented herein provides an efficient approach to as-built 3D modeling. As shown in the tests discussed earlier, it could be an effective way to model objects on construction sites, especially in view of its capability to update object information on a timely basis.

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