Human-Assisted 3D Spatial Modeling of Construction Sites Using Sparse Range-Point Clouds

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Abstract: 3D spatial-modeling can be used in various safety-enhancement applications and for as-built data acquisition in project-control systems. The objective of the research reported herein was to provide spatial-modeling methods that represent construction sites in an efficient manner and to validate the proposed methods by testing them in an actual construction environment. Algorithms to construct construction-site scenes and to carry out coordinate transformations in order to merge data from different acquisition locations are presented. Field experiments were conducted to establish performance parameters and validation for the proposed methods and models. Initial experimental work has demonstrated the feasibility of this approach.

Keywords: Sparse range-point cloud, 3D spatial-modeling, convex hull, workspace partitioning

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.

3D spatial-modeling methods that are currently in use, including 3D CAD and dense 3D scanning systems, have certain limitations, in that they are time consuming and labor intensive and require high performance computers. Models generated by 3D CAD system are very accurate, but the process is extremely time-consuming, primarily because of the time needed to make the measurements, which is done manually. In many cases, drawings of the site are not obtainable or do not match the as-built conditions. Furthermore, as modifications are made to the site—or equipment is added or moved around—many additional hours may be needed to construct a model of the site. These problems are exacerbated if data cannot be gathered because access to the facility is limited—on account of environmental conditions, such as the presence of safety hazards, or because the area is already occupied. For construction and maintenance of infrastructure, generation of a detailed, accurate model is not all that critical. In most cases, a collection of simple, primitive shapes will suffice (in fact, this is often the preferred approach).

There are major problems associated with dense 3D scanning systems that generate high-quality polygonal meshes from coordinate data for a set of scattered points [2]. Data obtained from laser scanning systems tend to be rather noisy and to contain errors that render most segmentation and modeling algorithms inadequate. The reconstruction of surfaces from unorganized point clouds derived from data obtained with a laser scanner is a very hard problem that has not yet been completely solved—and is especially problematic in cases where the data are incomplete, noisy, and/or sparse [11]. The process of converting an unstructured point cloud that represents the local geometry into a consistent polygonal model often requires days or even weeks [9], and typically consists of four steps: pre-processing, determination of the global topology of the object's surface, generation of the polygonal surface, and post-processing [4]. Because these point clouds can consist of millions—or even tens of millions—of sampled points, use of such a conversion process is mandatory in order to reduce the input complexity while maintaining a desired proximity [4]. The outcome is often far from ideal, however, since in many cases the 3D models created from the scans are still so large that even a high powered computer could be hard pressed to display the data in real time [10].

A recent study by Jaselskis et al. shows that laser scanning systems are not adequate for use in applications requiring high accuracy, such as in the measurement of the smoothness of asphalt surfaces [6]. The data they have compiled show that use of currently available laser scanning technology in real-time applications is problematic, on account of the long processing time required. Also, this study points up some drawbacks in the technology insofar as data acquisition and data processing are concerned.

The aim of the research described 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. SPARSE RANGE-POINT CLOUD APPROACH

While the dense point cloud methods including dense 3D scanning systems can produce very detailed models of the scanned scenes, which are useful for obtaining as-built drawings of existing structures, the burdens that they impose in terms of computation and data-acquisition time generally preclude the use of these types of laser systems for on-site, real-time decision-making. Modeling times for these laser range scanners can be on the order of hours or even days. In addition, it is virtually impossible to perform automated path planning based on their output, because of the exorbitant computational cost of considering each point of a surface in the vicinity of the equipment being used for a given task [5]. Despite certain disadvantages in using dense, 3D laser scanning, such as the lack of traceability, the high cost and large size of the equipment that is required, and the length of time needed for the processing phase [14], the most significant feature of any dense, 3D laser scanning system is its near-real-time capability to track moving objects or people.

In contrast to full-area, “dense”, range-point scanning, the use of sparse point cloud requires times on the order of only minutes or seconds for data acquisition and 3D modeling. Moreover, humans are adept at recognizing objects, especially in cluttered scenes such as construction sites [7], so by incorporating human perception into the overall modeling enterprise, an objective-driven, sparse point cloud approach has the potential to reduce not only the data-acquisition time but also the need for computationally intensive and/or expensive processing [3, 12].

Another characteristic of the sparse range-point cloud approach is the use of geometric primitives. Such geometric forms are ideal for modeling construction environments, since they require very little memory, even for large world maps, and they are easy to store and manipulate [11]. 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. In fact, the availability of a detailed local model to represent a construction-site scene is not critical. In applications that entail real-time obstacle avoidance, for example, the use of geometric primitives often suffices.

3. HUMAN-ASSISTED SPATIAL-MODELING

3.1 Process of human-assisted spatial-modeling

The process used in the spatial-modeling described herein is outlined in the flowchart in figure 1.

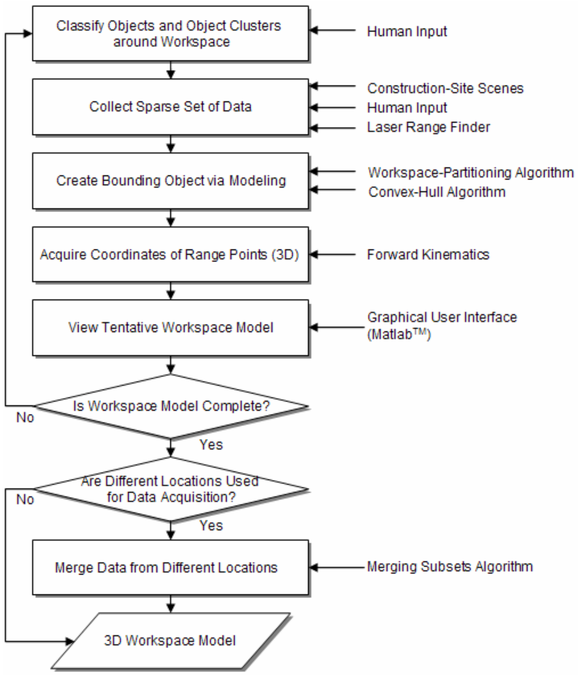


Figure 1. Flowchart of human-assisted spatial-modeling process

To acquire the spatial-information, humans first classify objects in and around the workspace and collect the range-point data that have been acquired with an inexpensive, single-axis, laser rangefinder mounted on a pan-and-tilt unit. Through the use of two general classes of geometric primitives (convex hulls and workspace partitions), bounding objects representing a wide range of construction-site scenes are created. Where more precise geometric primitives are required, object fitting and matching method can be incorporated, but it is not used here fore the sake of clarity. In cases where the operator’s view from any one reference point is limited and the coordinate data have to be acquired from two or more locations, the subsets of range points obtained from the different locations are merged into a single set before the site model is generated.

3.2 Algorithms for human-assisted spatial modeling

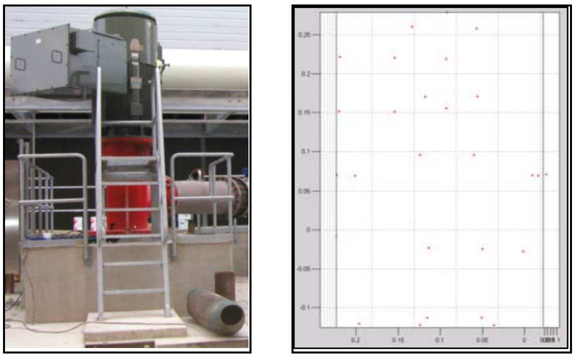
Given the types of objects most frequently encountered on a construction site, a wide range of construction scenes can be modeled by use of just a few classes of geometric primitives. Convex hulls and workspace partitioning are promising candidates for tools that can be used in modeling construction-site 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 convex hull and workspace partitioning are given below, followed by an explanation of the coordinate transformation which is needed for merging data that are acquired at different locations.

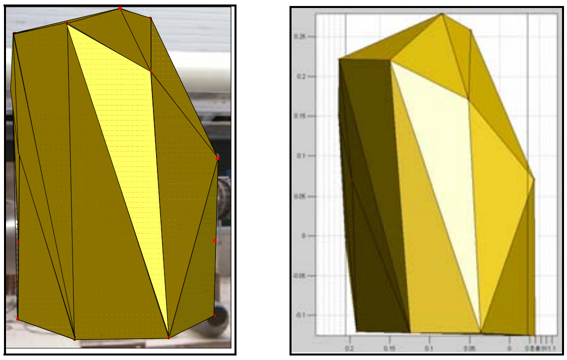
3.2.1 Convex hulls

In three-dimensional space, the convex hull of a set of points is the smallest convex volume that contains those points [1]. For the following reasons, the use of convex hulls is well suited to rapid spatial-modeling: (1) such volumes are inherently conservative, because of their convex nature, (2) any number of points can be picked, anywhere, and (3) the resulting hull is bounded by planar faces, thereby enabling rapid computation of distances [13].

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 [1]. The algorithm consists of three parts: initialization, partitioning, and iteration. A detailed description of the convex hull algorithm is given the article by Barber et al. An example of the convex hull modeling process is displayed in figure 2.



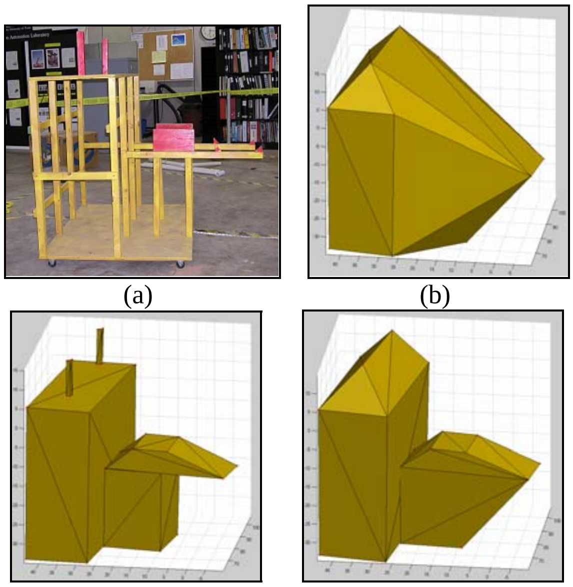
(a) (b)



(c) (d)

Figure 2. Convex hull modeling: (a) picture of actual object to be modeled, (b) scanned range points, (c) bounding object, (d) resulting convex hull

One of the benefits of using a convex hull algorithm in generating world models is that the user can set the level of accuracy of the model in accordance with their particular requirements. In the case of the pipe rack shown in figure 3 (a), three different models were generated: one that used a single convex hull (figure 3 (b)), one that was obtained by using two convex hulls (figure 3 (c)), and one that employed five convex hulls (figure 3 (d)). Clearly, the latter two models represent the object more accurately than the first model.



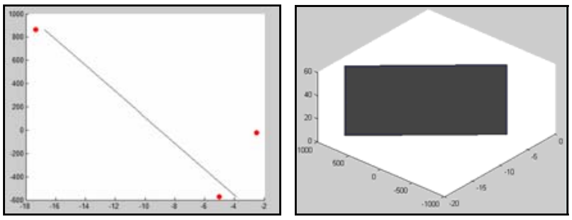
(a) (b)

(c) (d)

Figure 3. Variation in accuracy of models with number of convex hulls: (a) picture of actual object to be modeled, (b) model generated from one convex hull (c) model generated from two convex hulls, (d) model generated from five convex hulls

3.2.2 Workspace partitioning

An earlier research effort at the University of Texas at Austin proposed that a finite plane (or extremely thin wall) be used for partitioning a workspace (McLaughlin et al., 2004). 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. A detailed description of the workspace-partitioning algorithm is given in [12]. An example of the workspace-partioning algorithm is shown in figure 4.



(a) (b)

Figure 4: (a) scanned points and results of least-squares method (b) results of workspace partitioning

3.2.3 Merging model subsets from different locations

Because an equipment operator's view from any one reference point can be limited, multiple sets of range data may need to be used in modeling a workspace. Each set of range points is acquired at a different location, which serves as the origin of a coordinate system for that set of data. Since the range points from all the sets must be merged in order to model the workspace, their coordinates must ultimately be given with respect to a common coordinate system. The transformation is used to convert the components of a position vector from one coordinate system to another. Detail description of transformation is given in [8].

3.3 Data Acquisition Setup for Spatial Modeling

The coordinates of range points for various types of objects are acquired in three dimensions by using a laser with pan-and-tilt kinematics. The equipment used for data acquisition and modeling consists of 1) a laser rangefinder, 2) a two-axis pan-and-tilt unit (PTU), 3) the laser manufacturer's distance-data-acquisition software, 4) a tripod, 5) a C program that continuously reads pan and tilt angles from the PTU, and 6) modeling routines developed in Matlab^{TM} that display the models graphically via a graphical user interface (GUI). The hardware setup is portrayed in figure 5.

Figure 5. Hardware system

3.4 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 described 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 6).

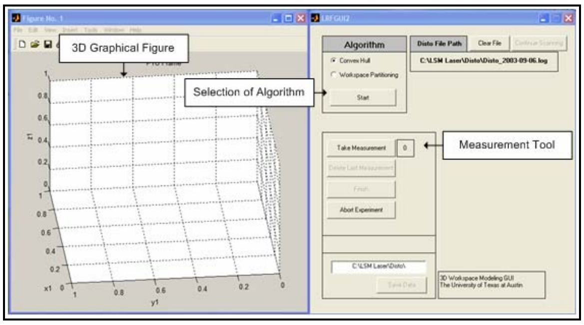


Figure 6. Graphical user interface

4. EXPERIMENTS IN SPATIAL-MODELING OF CONSTRUCTION SITE

An investigation of how well the modeling procedures described herein succeed in representing construction sites was carried out. An experiment on spatial-modeling of construction site was conducted. The site that was modeled is the cooling-tower construction site at the University of Texas at Austin was used as a test bed for the site modeling (figure 7). During the construction, a piece of equipment known as a heavy-lift was being used to lift pipes to the top of the object under construction.

Figure 7. Construction-site scene

This construction site, which is the workspace zone itself, is very narrow, so an equipment operator would need to exercise extreme caution in order to avoid obstacles and prevent accidents. This is a site on which safety of operation definitely cannot be guaranteed. In such an environment, an on-site spatial model could be useful, either to provide interactive visual feedback while a piece of heavy equipment is being operated or as a tool for 3D graphical simulation.

The construction-site scene was modeled using convex hulls and workspace partitioning. By use of a laser rangefinder, a few range points were selected for each object. During the object modeling, the time was measured (beginning with the registration of the first laser measurement and ending with the registration of the final laser measurement). Depending on the level of accuracy and complexity, it took anywhere from 15 seconds to about 2 minutes per object to collect the points, and less than 5 minutes to construct a model of the site scene. The results of spatial-modeling are shown in figure 8 and 9.

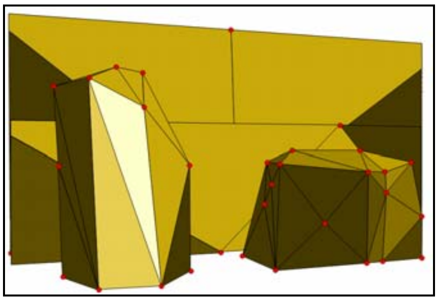


Figure 8. Results of spatial-modeling

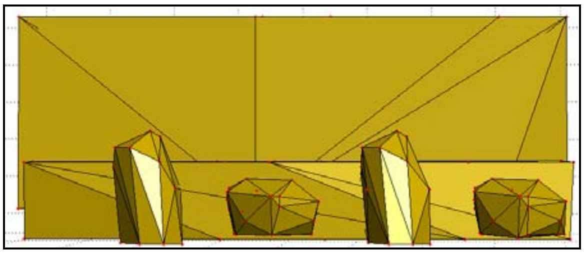


Figure 9. Results of spatial-modeling

5. CONCLUSIONS

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.

Various applications of the proposed modeling methods are being developed. An obstacle-avoidance system using the proposed 3D modeling approach appears especially promising because of the fast and efficient nature of the modeling; this system is already in the simulation stage. Also, 3D spatial -modeling with the use of a bounding model is expected to see effective use in a broad class of construction automation systems.

This research will eventually be extended to combine the sparse point cloud approach with the flash LADAR dense cloud approach to make up for some of the limitations of the former, such as in the representation of moving objects (including people), though such a combined system cannot be used for modeling per se. The possibility of using flash LADAR in conjunction with sparse range-point clouds is being studied.

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