A Motion Planning Software System for Automated Landfill Compaction on Rough Surfaces

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ABSTRACT

The integration of robotics and automation techniques in sanitary landfill operations would dramatically reduce construction workers' exposure to hazardous materials and improve the productivity of landfill operations. The autonomous equipment would provide a system where the productivity associated with waste spreading would be increased. Since there are uncertain job-site conditions in landfill sites, the stability of the autonomous compactor must be real-time protected. Another concern is the proper layout planning and utilization of the landfill space because it is an important resource for the landfill company. Productivity can be increased if the compactor can determine and apply the number of passes correctly by measuring on-site compaction density. This paper describes a software system developed to facilitate the generation of area-covering path plans of the autonomous compactor for the spreading and compaction processes on rough surfaces, the landfill space management associated with a proposed sensing system, and the recommended approach to determine the compaction density.

1. INTRODUCTION

Based on past experience throughout the United States and elsewhere in the world, land disposals in the form of sanitary landfills have proved to be the most economical and acceptable method for the disposal of solid waste[1]. Though the majority of technical waste management issues deal largely with chemical processes, techniques, and geotechnical design, sanitary landfills require new construction engineering management skills as well.

One of the major concerns with solid waste handling is the potential long-term health risks faced by manual workers/operators from constant exposure to the toxic solid, liquid, and gaseous by-products produced by the decomposing waste materials in the landfill site. Another area of concern is the proper layout planning and utilization of space in jobsites. Since the unused capacity of a landfill site is a resource, the landfill company will try to minimize the unused portion. To improve the productivity of waste spreading and compaction processes, it is important for the compactor operator to follow an efficient motion pattern and know that adequate compaction has been attained. Therefore, developing optimal motion planning and measuring on-site compaction density are key issues to reduce the required compaction time.

Robotics and automated technologies offer a new approach to deal with the above concerns. Developing autonomous equipment (i.e., remotely controlled and operated) would dramatically reduce workers potential exposure to hazardous materials. At the same time, autonomous equipment would increase productivity by using special sensing equipment. The productivity of the landfill would be increased because of better space management through optimal path planning. This unique ability to increase safety and decrease voids in the landfill at a lower cost makes the application and development of robotics and automated technologies highly desirable for landfill operations.

Automation of processes, such as the spreading and compaction of waste and cover material in a landfill site, requires an efficient operation planning system to generate an area-covering path that facilitates autonomous movement of compactors. Tserng et. al, 1995[2] studied and developed an automation system to assist in the design of landfill cells and the generation of an area covering path for an autonomous compactor for smooth surfaces. Typically, a given landfill site can be partitioned into *cells* using a probabilistic model for waste generation. The configuration of the landfill site is partitioned into a *quadtree* data structure by employing a recursive spatial decomposition technique. A recursive sub-division of each cell into *monominoes* facilitates the system to automatically deal with any deviation in the actual volume of waste. Within the monomino, the motion path of the compactor can be made by several motion models including: *Straight-Up*, *Straight-Down*, and *Zig-Zag* motion models[3].

Since there are uncertain job-site conditions at landfill sites (i.e., changing profiles and trough surfaces), the balance of the autonomous compactor must be real-time controlled. In addition, the landfill should be maintained to ensure a smooth surface. This paper describes a software system that deals with the rough surface. Furthermore, the positioning system, space management, and measurement of waste density involved with the developed software will be discussed.

2. PROBLEM STATEMENTS

When developing a motion planning system for autonomous landfill compactor in rough surfaced terrain, the following problems may be encountered.

- *Rough Surfaces and Variable Volume of Waste Dumped from Truck*

  As shown in Figure 1, there are two principal methods used to spread and compact waste in a working face: (1) unloading solid waste at the toe of the slope and spreading and compacting the solid waste from the toe of a slope to the top of the slope, and (2) unloading solid waste at the top of the slope and spreading the solid waste and compacting from the top of the slope to the bottom of the slope[4]. Due to the uncertainty of the landfill surface, the landfill surface information is incomplete for the motion planning system during the autonomous waste compaction. If the autonomous compactor does not realize the surface condition, the waste will not be homogeneously distributed by the compactor (see Figure 1a). Also, if the compactor doesn't have an appropriate path plan for spreading the waste, the landfill surface will become rougher as more passes are made. Therefore, the waste spreading process is an important factor in influencing the uncertainty of the landfill surface. Furthermore, because of varying truck sizes and different types of waste material, the volume of waste dumped per truck load will change. The truck load is measured only by weight; therefore, it is hard to determine the volume of waste carried by a truck if it is not enough for one complete pass, as depicted in Figure 1b. This situation will make the surface more difficult to control because the compactor cannot move waste to finish the complete working slope.

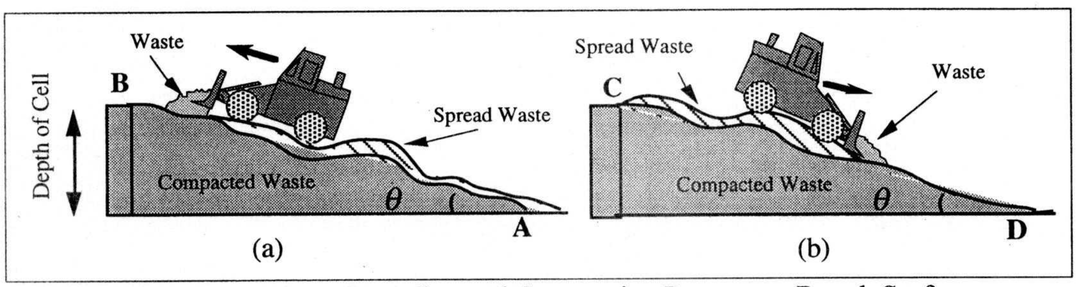

Figure 1: Waste Spreading and Compaction Process on Rough Surfaces

- *Space Management*

  Since unused landfill space is the real commodity for landfill companies, space management must be optimized. Finally, solid waste operations are a dynamic process where many pieces of equipment, crews, and robots move about. Unless properly addressed, congestion and interference could seriously hamper production and possibly waste landfill space. Proper space scheduling and management offers substantial benefits in terms of expanding the life time of landfill site as well as avoiding the congestion and conflict of multi-vehicle operations.

- *Mapping System*

  The mapping and positioning technologies are the key issues for navigating the autonomous compactor. The mapping system also assists in developing the space management system. For instance, the occupied space can be obtained by the real-time update of the autonomous compactor's position.

- *Methods for Measuring Waste Density*

  In conventional operation, the waste is assumed to be homogeneous in the landfill. Therefore, the compactor uses the same number of passes across the landfill. However, this is not an efficient method. Productivity can be increased if the compactor can determine and apply the number of passes correctly by measuring on-site compaction density.

3. RESEARCH METHODOLOGY

In response to the problems presented and discussed above, recommended methodology and suggestions are presented below.

3.1 Sensing System to Understand Surface Conditions

Because of the inherent uncertainties in the landfill surface, the waste must be homogeneously distributed by the compactor. If not, it will become increasingly difficult to handle the dynamic stability of the autonomous compactor on rough surfaces. Figure 2 shows the motion planning software system used for this research and the proposed sensing system for understanding the surface condition. If the compactor has two base-inclination converters (see the right-upper window of Figure 2) to detect the orientation information of the compactor, the autonomous compactor can obtain the orientation angles (α, β) of the compactor. In addition, the high-precision compass provides the rotation information of the compactor (see the right-upper window of Figure 2). The Global Positioning System (GPS) provides the compactor's location in the landfill configuration. By combining the location coordinates, rotation angle, and the base-inclination angles of the compactor, the surface condition of the four wheels can be presented using the transformation techniques.

Based on the sensing system proposed above, the compactor's stability can be protected by a safe range of base-inclination angles that can be calculated exactly from a mathematical model[5]. Referring from the exact range of safe base-inclination angles, users can input their designed safe range by selecting Base-Inclination Angle item from the Sensor menu. In this automation system, there are two stage of motion approach: (1) *Autonomous-Navigation* Stage and (2) *Joystick-Control* Stage. When the base-inclination angle is inside the safe range, the autonomous compactor is in the *Autonomous-Navigation* Stage. In this stage, the compactor operates the waste spreading and compacting processes automatically. When the compactor comes close to a stability-loss position (i.e., big holes, sharp slope, or instant obstacles,...etc.), a warning signal will sound and the system switches to the *Joystick-Control* Stage. In this stage, the remote operator can navigate the compactor to deal with the problem by joystick via vision-aided monitor.

After the computer moves to the top of the slope, the whole surface condition of the strip can be approximated. As the compactor crosses the working face, the sensory feedback for each position can be stored into a specific data structure which will be described in the next section. Consequently, the surface conditions of the entire working face can be understood.

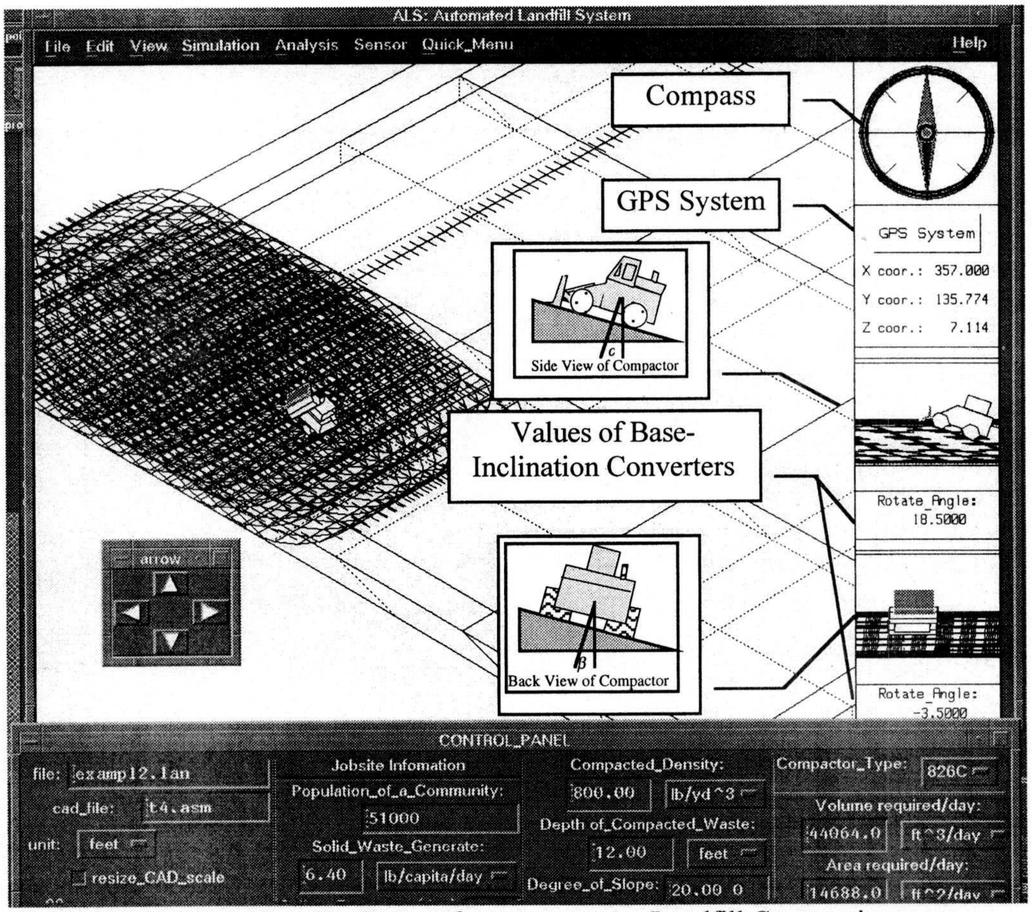

Figure 2: Sensing System for Autonomous Landfill Compaction

3.2 Partition Working Surface by Spatial Decomposition Technique

In spatially decomposing a landfill site, the *quadtree* and *B-tree* data structure are employed together to partition the landfill into small working areas. As shown in Figure 4, the entire data structure has three major levels: *cell* level, *monomino* level, and *strip* level. In cell level, the landfill site can be partitioned into cells using a quadtree structure. The tiling of a cell is performed by monominoes whose dimensions depend on the characteristics of the compactor and the size of the landfill site. The waste compaction within one monomino can be completed by several circles of a motion model. Using B-tree structure, one circle of a motion model (e.g., Zig-Zag model, see Figure 3) can be divided into several strips and sections by the time elapse of the kinematic GPS system.

Consequently, the surface information of each section can be restored into every leaf of the entire data structure, and the surfaced terrain of working places can be obtained.

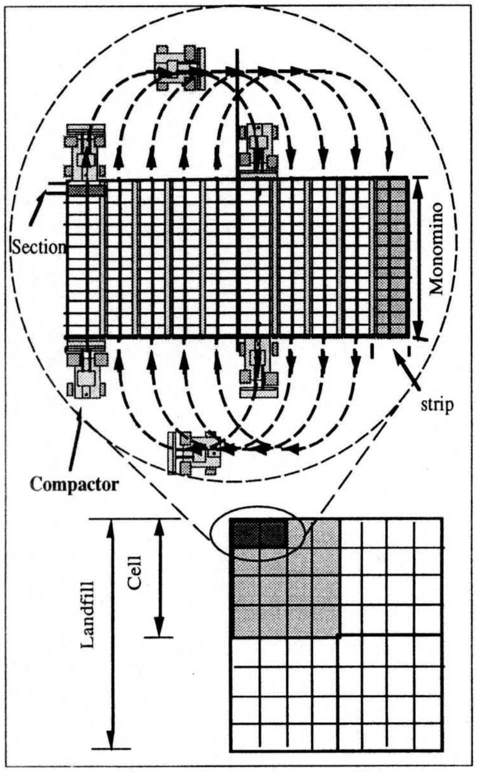

Figure 3: Partition of Landfill Side

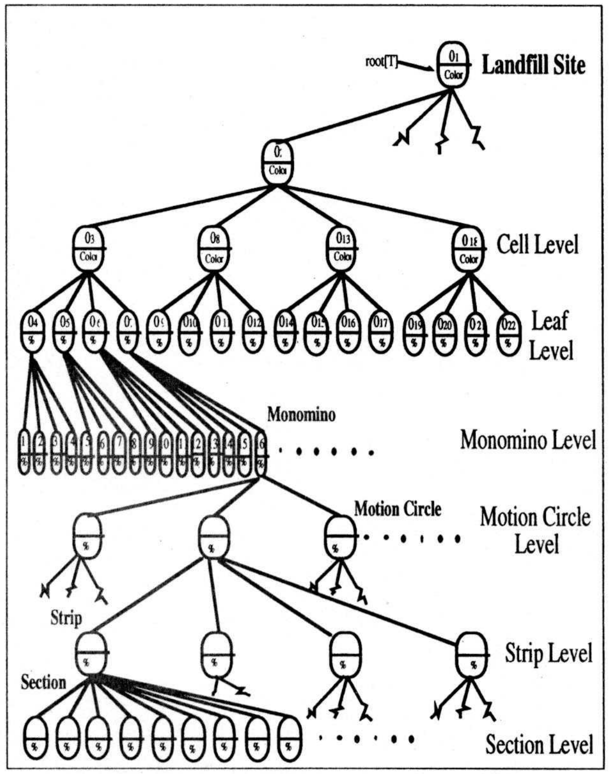

Figure 4: Data Structure of Landfill

3.3 Motion Strategy to Deal with Various Volume of Waste

Based on previous strip surface information along the slope, the compactor will move the waste into the sections containing the least waste (Figure 5a). To deal with the varying volume of waste dumped from a truck, the compactor can spreading the waste into the empty sections in the next circle of spreaded waste (Figure 5b). These improvements to the waste spreading process would make the landfill surface smoother. Following this, the surface would always be maintained to minimize the surface uncertainty.

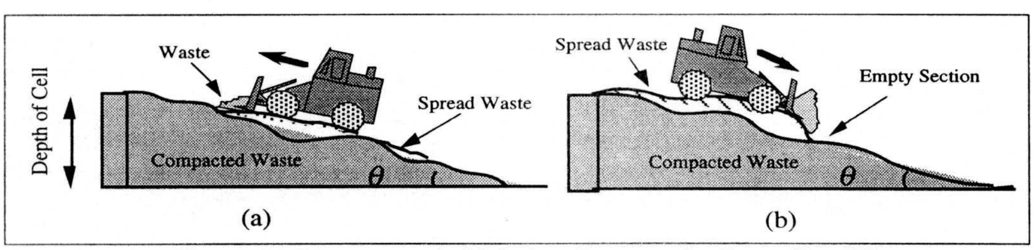

Figure 5: Recommended Motion Strategy for Spreading Waste

3.4 GPS System to Success Motion Planning and Space Management

Another important function of the mapping and navigation system is controlling the compactor's movement throughout the landfill. Knowing the compactor's location is essential for the remote guidance of the landfill compactor. By placing landfill coordinates on a computerized grid network, it will be possible to guide the compactor to desired coordinates along a designated path. This system can save time, operator input, and help in raising productivity. Global Positioning Systems (GPS) are space-based radio positioning systems that provide 24 hour three-dimensional position, velocity, and time information to suitably equipped users anywhere on or near the surface of the Earth[6].

Ideally, the GPS antenna can be installed on the compactor. By using the real-time and kinematics GPS system, the location of the compactor can be determined with great precision. Simultaneously, the motion of compactor can be displayed on the computer screen by transferring the location information to the computer. The whole structure of this mapping system is shown in Figure 6. Based on the integration of GPS and the specific data structure of Section 3.2, the capacity information of every section can be real-time presented in 3-D configuration to assist in space management (see the zoom window of Figure 6). In addition, the autonomous compactor can locate the proper working place to compact waste by a recursive traversal method along the data tree (Figure 4).

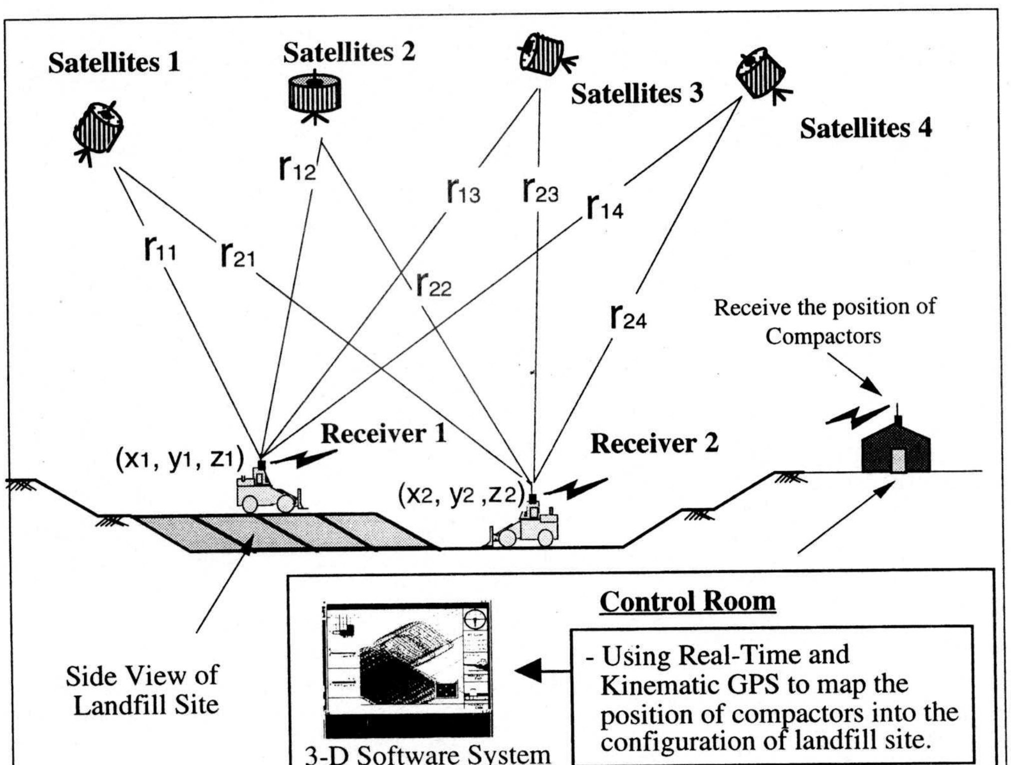

Figure 6: Kinematic GPS and Landfill Space Management Systems

3.5 Method to Determine Number of Passes

It is important for the compactor operator to know that adequate compaction has been attained. By determining on-site compaction density, the number of passes can be optimized and spurious passes avoided. Because the waste is not homogeneous, determining the target density is difficult. However, an alternative approach that works effectively is to measure the change in the z-coordinate from the angle of base-inclination converters or by the GPS system. If the z-coordinate stays relatively constant as the compactor moves back and forth along the slope, then adequate compaction has been achieved and the compactor should move to the next work place.

4. SYSTEM IMPLEMENTATION AND DESCRIPTIONS

The 3-D animated simulation software system for autonomous landfill compaction is implemented by using the PHIGS[7] graphical industry library and MOTIF toolkit library with C-program linking. PHIGS provides the necessary environment of a X-window system for hierarchical graphic models that allow an application programmer to describe a graphic model without having to deal with the hardware details for producing the model on a display device. MOTIF[8] is based on the X Toolkit Intrinsics (Xt) of the X-window system and offers functions to produce user-friendly interfacing objects such as windows, menus and icons.

This motion planning system not only assists in compaction process planning, but supports geometric design of landfill cells and landfill space management. During the input stage, the configuration of the landfill site can be created using any commercial CAD modeling package that provides ASM graphical format. It can be loaded by selecting the *Open* option under the *File* menu as shown in Figure 7. After obtaining the input pertaining to the landfill design and environmental information in the *Control Panel* window, the landfill site can be partitioned into cells and monominoes using the recursive decomposition algorithm[3] by selecting the *Cell* and *Monomino* items from the *Analysis* menu.

Multiple-views of the landfill site can be tiled together by varying the orientation of the *view reference planes* for the tiled windows. The example screen shown in Figure 7 depicts a plan-view, an elevation, a front-view, and an isometric view of the landfill site at the same time. Under the *View* menu, the *Zoom-In*, *Zoom-Out*, *Pan-Around*, and *Pan-Over* functions can be selected to zoom, rotate, and translate the entire 3-D model into the desired view during the animated simulation. Right-side windows present the values for compass, GPS system, and base-inclination angles. In addition, two windows are designed to zoom close to the side and front view of the compactor in order to monitor the details of the waste compaction process.

By selecting the *Simulation* menu, the motion path and cover surfaced terrain of the compactor's motion within cells and monominos will be presented in 3-D animation. As the compactor compacts the waste along the slope, the number of passes are determined by the difference of values of z coordinates between passes. In addition, the autonomous compactor will traverse the quadtree and B-tree data structure to locate the proper working places for the efficient space management.

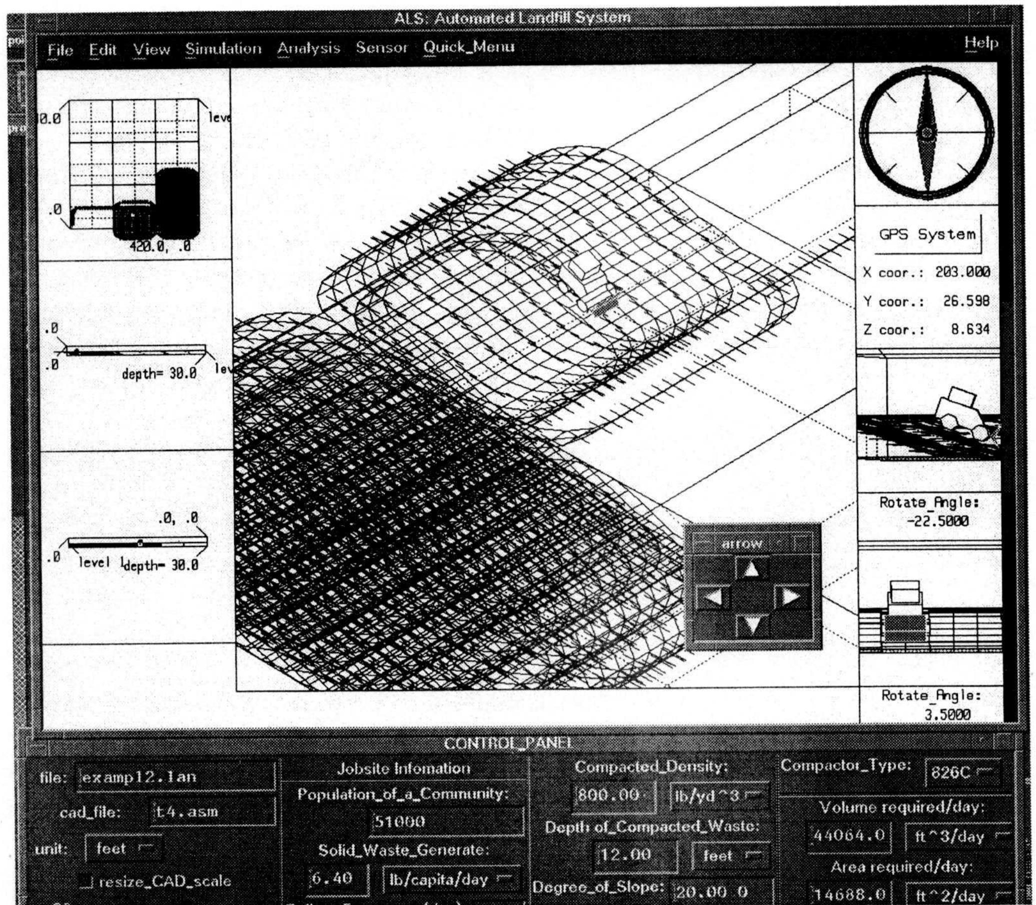

Figure 7: Multi-View Window of Animated Simulation System

5. CONCLUSION

In this paper, the critical ideas necessary for developing autonomous methods for landfill compaction are presented and discussed. The proposed methodology addresses two concerns of landfill managers: (1) manual operators a safety risks and (2) optimum management of precious landfill space. Using the ideas presented, a 3-D animated simulation software system was developed and presented. In the future, this research could be expanded to develop a motion planning system for multi-vehicle landfill operation including the relative motions of trucks, compactor, and crawler-tractors.

6. REFERENCES

1. General Electric Company, (1975). Solid Waste Management, Van Nostrand Reinhold, New York, N.Y.
2. Tserng, H. P., Kunigahalli, R., and Russell, J. S., (1995). "OPSALC: An Operations Planning System for an Autonomous Landfill Compaction," Proceedings of Twelfth International Symposium on Automation and Robotics in Construction, May 31-June 2, Warszawa, Poland, pp. 63-69.
3. Tserng, H. P., Veeramani, D., Kunigahalli, R. and Russell, J. S., (1996). "OPSALC: A Computer-Integrated Operations Planning System for an Autonomous Landfill Compaction," *International Journal of Automation in Construction*, in press.
4. Tchobanoglous, G., Theisen, H., and Eliassen, R., (1989). Solid Waste: Engineering Principles and Management Issues, McGraw-Hill, Inc., New York, N.Y.
5. Dudzinski, P., Cieslak, R., and Pieczonka, K., (1995). "Dynamic Stability of Machines with Articulated Frame Steering in Automatic Warning System Aspect," Proceedings of Twelfth International Symposium on Automation and Robotics in Construction, May 31-June 2, Warszawa, Poland, pp. 299-306.
6. Wolf P. R., and Brinker R. C., (1994). Elementary Surveying, HarperCollins College Publishers, New York, N.Y.
7. Gaskins, T., (1992). PHIGS Programming Manual, O'Reilly & Associates, Inc., Sebastopol, CA.
8. Heller, D., and Ferguson, P. M., (1994). MOTIF Programming Manual, O'Reilly & Associates, Inc., Sebastopol, CA.