The State of the Art in Automation of Earthmoving

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Abstract

A recent trend towards greater automation of earthmoving machines, such as backhoes, loaders, and dozers, reflects a larger movement in the construction industry to improve productivity, efficiency and safety. This document reviews related work in various disciplines drawn upon by researchers— soil mechanics, computer graphics, kinematic and dynamical modeling, optimization, control and decision theory. A taxonomy is suggested into which various automated systems reported in the literature, can be classified.

Key Words: automation, earthmoving, excavation, soil-tool interaction, kinematic and dynamical modeling, tactical and strategic planning, tele-operation, trajectory control.

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1 Introduction

Industries such as mining and construction in which earthmoving plays a fundamental role are constantly under pressure to improve productivity (amount of work done), efficiency (cost of work done in terms of labor and machinery), and, safety (injury sustained by workers). Automation offers the possibility of contributing to each metric but has been slow in being accepted. Until recently, it has been possible to make gains using traditional means—over the last four decades earthmovers have become progressively larger and their mechanisms more efficient. Also, automation of fieldworthy earthmovers is a difficult problem. These machines must operate in unstructured, dynamic, outdoor environments, often in poor visibility conditions and inclement weather. However, after decades of increases in size and power, practical limits have been reached and now automation is being sought for further improvements. At about the same time, several enabling technologies relevant to earthmovers, particularly in the area of environmental perception, are becoming reliable and affordable. Computing technology has also reached the stage where fast, compact and rugged components can match the bandwidth of sensory data.

Beyond the industrial arena, which is motivated mainly by economic considerations, automated earthmoving machines are needed in worksites that are hazardous for humans. For example, NASA is interested in setting up lunar and martian habitats for humans, and it is expected that automated excavators will do much of the work before humans arrive [Bernold 89, Register 90, Toups 90, Boles 90]. Another example is in the remediation of waste sites where chemical and nuclear wastes are stored [Wohlford 90, Burks 92, Thompson 95]. The net effect is that the past decade has seen a groundswell of interest in automation of earthmoving, and the trend is accelerating.

The cycle of operation for a fully autonomous machine is: *sense*, *plan*, and *execute*. First, an automated machine must sense its own state and the world around it. Next it must use this information along with a description of a goal to be achieved to plan the next action to be taken. In some cases the mapping from sensing to action is direct, and, can take the form of a pre-determined control law. In other cases, deliberation, or the use of models (sensors, mechanisms, and, actions) is necessary. Finally, the action must be executed via the mechanism. Since, relatively few systems are fully autonomous, depending on human input or control to achieve some of their function, this article examines various aspects of the enabling technologies used by partially automated systems. We will examine automation of mechanisms (for example in Figure 1) that actually engage the terrain and displace soil, but appli-

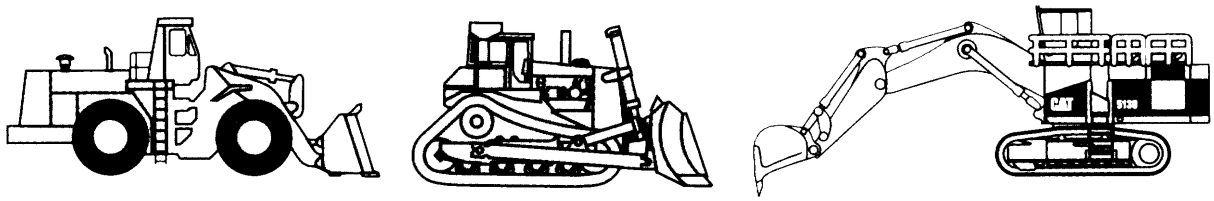


Figure 1 Three examples of earthmoving machines (a) wheel-loader (b) bulldozer (c) backhoe excavator.

cations such as haulage and roof-bolting are not discussed.

We start with a brief summary of sensing technologies as they pertain to earthmoving machines and the environments in which they operate. Next, we examine the various models used either to design better implements, determine control laws, or, as tools for deliberative planners. In specific, we examine models of machines and their interaction with the earth. These formulations are straightforward implementations of methods developed for robot manipulators. A less well understood area is that of soil-tool interaction, but core ideas from models developed by researchers in soil mechanics can provide important insights. Planning and execution are discussed via a survey of systems and methods reported in the literature. These systems are placed in a taxonomy based on the level of autonomy. At one end are tele-operated systems. These systems depend on a human operator for every motion. At the other extreme are systems that can sense, plan, and act on their own.

2 Sensing

Two broad classes of sensing technologies support earthmoving automation. One class allows determining the state of the machine itself, both with respect to some local coordinate frame and with respect to some fixed, world-reference frame. The other class of sensing concerns perception of the environment around the earthmover. A third class of sensing concerns provision of perceptual feedback to operators particularly in the case the case when the operators are located remotely [Labonte 94].

Local state is achieved by measuring displacements at a machine's various joints (rotary and prismatic). Typically such sensing is used for control—it provides feedback to keep mechanisms on a reference trajectory. Instrumenting earthmovers with joint sensors is not trivial, since sensors will often be subjected to large forces. The most common method to sense joint angles is to use position transducers inside hydraulic cylinders that cause the rotary motion (Peussa 95 and Corke 97a). The advantage of such sensors is that they are robust, but the downside is that position sensing can be noisy. At the risk of decreased robustness, an alternative is to use joint resolvers directly at rotary joints. Resolvers, like potentiometers produce a signal that is proportional to joint displacement. Mulligan et al. report a novel scheme to compute the joint displacements from images of an excavator linkage using geometric models of an excavator arm coupled with fast processing [Mulligan 89]. The main difficulty with such a scheme is placing cameras to cover the entire work envelope.

Another form of state estimation is to locate an earthmover with respect to some fixed coordinate frame. It suffices to say that many sensing modalities have been used, including GPS, inertial sensors, and reflecting beacons [Wells 86, Smith 88]. Successful estimation schemes combine vehicle models with complementary sensing modalities.

The other class of sensor perceives the machine's immediate environment so that it can intelligently perform tasks such as avoiding obstacles or picking a place to dig. Progress in this area is critical for automation of many systems that must operate outdoors in all kinds of weather and lighting conditions. Two promising technologies for environmental sensing are laser and radar ranging. In both cases, energy is transmitted into the world and range is determined by processing the reflected signal. While neither technology is fully mature, recent results are encouraging. Scanning laser ranging can provide accurate and high resolution range images as shown in Figure 2 to determine the shape of the immediate environment.

For example, the type of image shown above can be easily transformed into a topological map of the terrain such as shown in Figure 3. Sarata has also proposed using a scanning laser scanner to determine the shape of an ore pile [Sarata 93].

Laser ranging will likely become cheaper, more accurate and faster—commercial prototypes of laser scanners operating at 500 Hkz with millimeter accuracy are already available—but the main issue is whether such sensors can be made to operate in the dust, smoke, and precipitation commonly found at worksites. Millimeter wave radar on the other hand promises performance that is not degraded by such environmental conditions. Everett

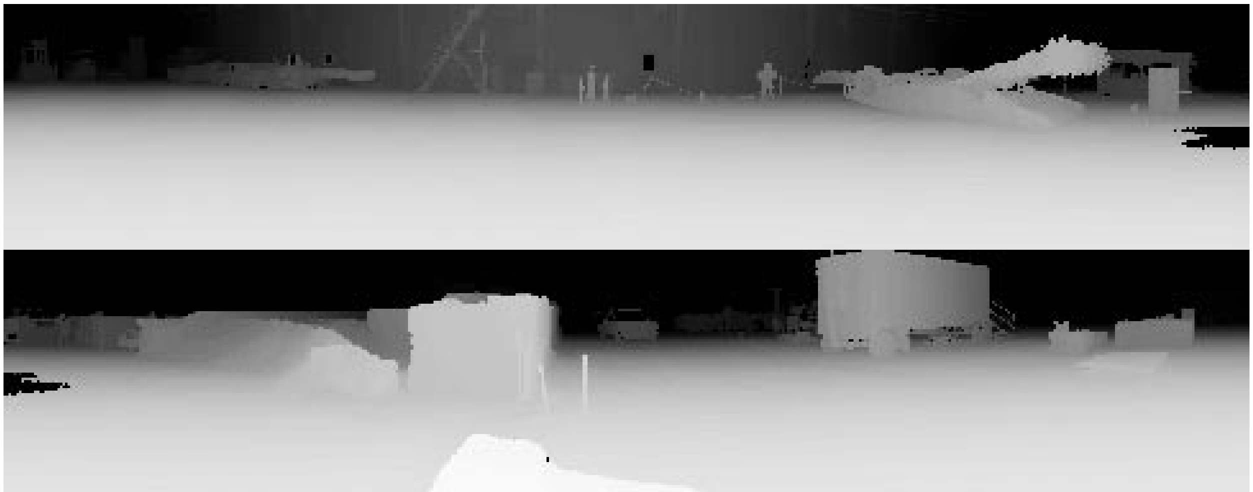


Figure 2 High resolution range image of a construction site from a commercially available panoramic laser scanner. Each strip represents a 180 degree field of view. Each image pixel corresponds to the range from sensor to world objects. The laser is pulsed at 40 kHz. Maximum range is 20 m. Accuracy +/- 5cm.

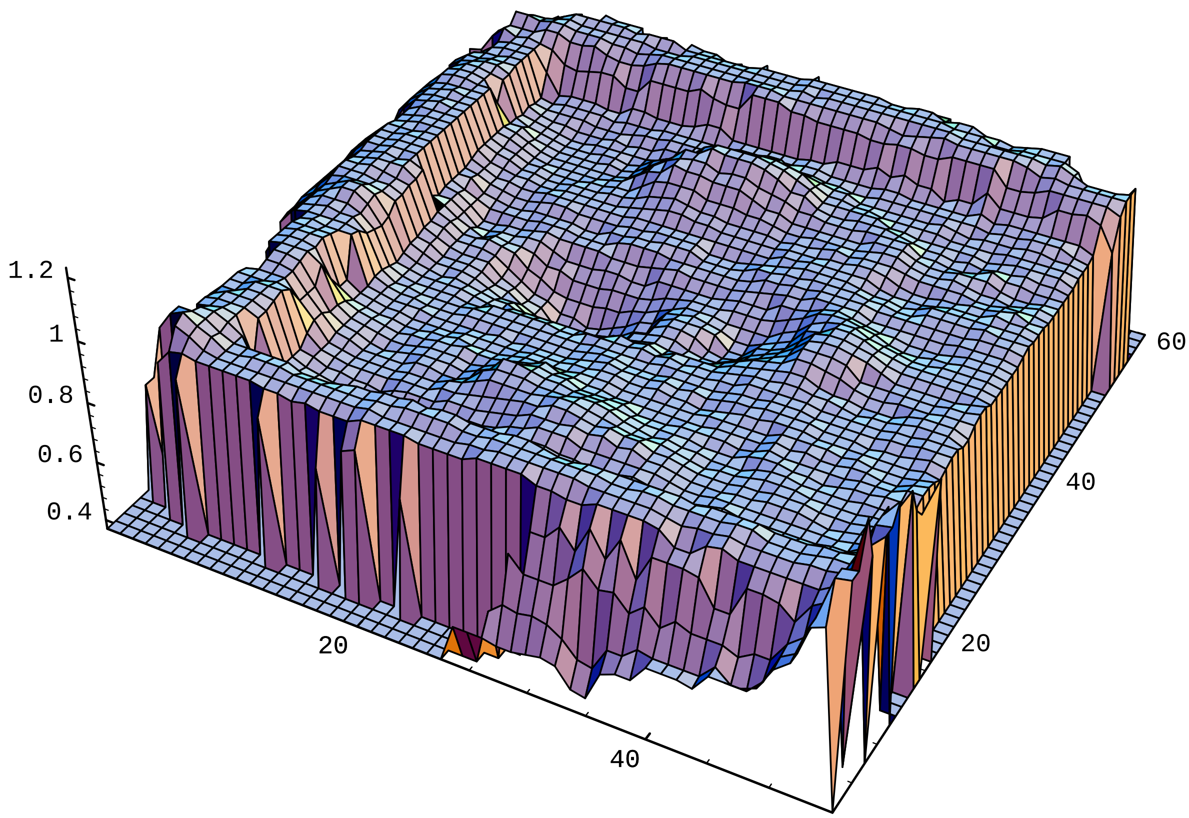


Figure 3 An elevation map of a soil bin (approximately 2.5m x 2.5m) constructed with data from a scanning laser using a mapping system developed at Carnegie Mellon [Hoffman 92]. Each cell in the terrain map is 5 cm square.

reports numerous radar systems aimed at satisfying short distance non-contact ranging needs [Everett 95]. The greatest concern with this modality is resolution. While down-range accuracy is generally high, the cross-track accuracy suffers due to the broad transmitted beams. Even with the broad beams, it is possible to do successful obstacle avoidance as described by League and Lay [League 95]. They have proposed using a scanning radar to avoid obstacles. Instead of using the first return that exceeds a preset threshold, the entire return signal is analyzed and each pixel is separated into hundreds of range bins. Obstacles are distinguished from ground clutter by integrating returns over several frames.

Another active means of ranging uses ultrasonic sensors to determine distance to objects in the world. Although these sensors have seen greater use on indoor robots, ultrasonic sensors have been used outdoors for tasks such as collision avoidance for autonomous vehicles [Langer 92]. They have also been proposed to measure terrain elevation as it is graded [Teach 93]. Placed behind the bulldozer blade, the sensors provide a continuous elevation survey and the resultant contour map is displayed to an operator in the vehicle.

In contrast to active sensors that transmit energy into the world, passive ranging devices use available energy to calculate range. Corke et al. have reported numerous sensing modalities including fast stereo vision for mining environments [Corke 97]. Takahashi has also used a passive vision system to reconstruct the shape of piled rock fragments [Takahashi 95a, Takahashi 95b].

3 Models

Here we examine models of mechanisms, and, of soil-tool interaction. Such models have been used for machine design and to construct control laws that relate sensed quantities to actuation. Less commonly, models have also been used by deliberative planners to simulate on-line, the effect of future actions. The models in question come in two flavors. The first type are *kinematic* and encode purely geometric relationships. For example, an earthmover, such models relate joint angles to the positions of the various links. The second type of model is *dynamical* and encodes relationships of quantities such as mass, friction, cohesion, and the forces required to accelerate bodies. For example, such models relate motion of a mechanism to the torques applied at the joints. In some cases, the analysis is restricted to forces that are required at equilibrium, ignoring forces required for acceleration. Such *static* models are simpler but more approximate.

3.1 Kinematic Mechanism Models

Several researchers have worked out the kinematic relationships that relate joint angles of a backhoe to the pose (location and orientation) of the bucket's tip [Seward 88, Vaha 91a, Koivo 92, Bernold 93]. Hemami and Daneshmand have developed a similar kinematic model for a front loader [Hemami 92a]. Since most excavator mechanisms are not directly driven at the joints, but rather are powered by hydraulic cylinders attached to the limbs of the machine, researchers have further developed the relationships between the joint angles and cylinder positions [Koivo 92, Hemami 92a, Takahashi 94b].

The forward kinematic relationship is used mainly in visualization for humans and in forward simulations of the joint trajectories. On the other hand, given a desired pose of the bucket, the inverse relationship provides the joint angles necessary to achieve the pose. Further, the inverse relationship provides a method to determine if a hypothetical pose of the bucket is reachable. A particular pose might not be reachable because it requires joint angles beyond the limits of the machine, or, because it is outside the workspace of the robot. The kinematic analysis can be carried further in order to relate velocities and forces at the bucket tip to velocities and forces experienced at the joints. Hemami and Daneshmand have suggested such an equivalent model for a wheel loader [Hemami 92a].

3.2 Dynamical Mechanism Models

While kinematic models employ a purely geometric basis, dynamical models try to capture considerations such as inertia, friction, and acceleration. The purpose of such models is to relate joint torques to the motion of the excavator's limbs. The forward model is used for simulation— given joint torques, it predicts the motion of the entire machine. The inverse dynamic model offers greater utility. It provides a reference joint-torque trajectory given the desired end-effector motion.

Vaha and Skibiniewski have proposed a model based on the Newton-Euler method of dynamical modeling for robot manipulators [Vaha 91b, Vaha 93a]. Lawrence et al. have also used a similar formulation to model an excavator backhoe modified for forestry applications [Lawrence 95]. Sarata et al. have proposed a Lagrangian formulation of wheel loader dynamics and have modeled the machine as a three link manipulator [Sarata 95]. These models are meant to capture second-order effects of inertial (centripetal and coriolis) forces due to the linkage mass and end-effector load. They are chiefly relevant for trajectory control when the bucket is moving through free space, as opposed to the terrain. To date, there has been no reported work on inverse dynamic methods that explicitly model the resistive forces encountered while digging in order to produce a stable trajectory control. Hence, the resistive forces during digging must be considered as a disturbance. An important effect that has remained unmodeled is the effect of limited flow of hydraulic fluid. Often, when one joint is in motion, fluid flow to other joints is decreased and the links follow a modified trajectory.

Tafazoli et al. have proposed a method to estimate the inertial and friction parameters of an excavator linkage [Tafazoli 96] based on force measurements at the load pins of the hydraulic cylinders and given known weights applied to the bucket. The authors report that this model can predict bucket payload to within a few percent. Corke et al. report a dynamic model for dragline swing control and present a PD controller to stabilize the oscillations of dragline buckets which can have payloads of up to 100 tons.

Scheding et al. have proposed a dynamic model of a Load-Haul-Dumper (LHD) that includes forward and lateral slip [Scheding 97]. They show how this dead-reckoning model can improve position estimation over a method that simply integrates data from inertial sensors when the vehicle is moving on uneven ground.

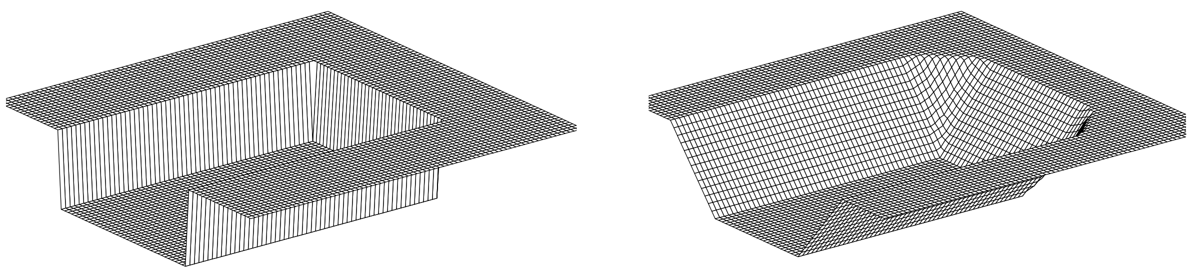
3.3 Soil-Tool Interaction

By its nature, excavation involves forceful interaction with terrain. The nature of this interaction is most influenced by soil properties and soil behavior is a very complex phenomena. Some soils behave like liquids and other like solids. Soils can behave anisotropically, that is, in situ, soil characteristics can vary substantially with the direction in which forces are applied. Also, as anybody who has dug a hole in a garden and tried to put the soil back into the hole later knows, the state of soil can vary tremendously. Intuitively, it is obvious that digging in loose, dry sand is very different from digging in a compacted, clayey medium. Indeed, this difference can be so large that strategies for digging in various media differ radically. Ideally, we would like to model the full effect of a tool moving through soil. At the very least, we would like to know the effect of the terrain on the tool. That is, we would like to characterize the interaction between a tool (bucket or blade) and soil. The literature in this area focuses on two major issues.

The first question is: what happens when a bucket sweeps along a trajectory in the soil? Specifically: what forces are involved; how does the soil move and settle; and, how much of the soil ends up in the bucket? Unfortunately, no closed-form models exist to answer such questions since soil is complex enough that the differential equations required to describe evolution of the soil mass over time are local, not global, in their effect; numerical integration must be used to determine evolution. The second question is: what is the effect of the terrain upon the tool? That is, what resistive forces does the bucket experience as it excavates. A resistive-force model can be used to limit the motion of an earthmover to actions for which the necessary torques can be generated. It can also be used to model the closed-loop behavior of a control law that uses measured resistive forces to control bucket trajectory.

Both questions posed above can be answered by using finite element methods (FEMs). FEMs provide a method to model systems composed of many (possibly irregular) elements with a large set of partial differential equations. A number of researchers have used FEMs to answer the questions posed above [Cundall 88a, Cundall 88b, Yong 77]. Yong and Hanna have specifically studied the performance of a flat blade moving through short distances (less than one foot) in clay soil. They developed a FEM that provides detailed information on the stress and deformation of the soil as well as the forces developed at the tool. The advantage of these methods is that they enable estimating both forces experienced by the bucket as well as deformation of the terrain. Unfortunately these methods are so computationally taxing that their use can be prohibitive for any purposes beyond off-line simulation. Since a single FEM prediction might take minutes to compute, such methods do not offer a tractable approach for on-line evaluation.

If requirements are relaxed, however, the finite element methodology becomes more attractive. For instance, if an approximate model of soil motion, especially settlement of dry uncompacted media, is required it is possible to use some methods inspired by finite element analysis. These methods represent the world as a two or three-dimensional grid of discrete elements. Iterative algorithms are applied to the grids until equilibrium is reached. For example, Homma et al. propose a volumetric model to simulate the settlement of soil [Homma 90]. Terrain is tessellated into a three dimensional grid and each cell is marked as occupied/empty. At every step of the simulation, each grid cell is checked to see if the contents will stay unchanged, or move to another cell, using a few simple rules. The rules are repeatedly evaluated until all cells achieve equilibrium. This method is slow simply because it is three dimensional and requires treatment of a large number of cells. Puhl has described a similar method that assumes that the elevation of terrain is a single-valued function, that is, there are no voids [Puhl 92]. This simplification allows a two dimensional treatment of the soil surface and is, hence, much faster (quadratic instead of cubic). Figure 4 shows how a modified version of this method described in [Singh 95a] could be used to predict settlement of soil after removing a specified volume. While the method assumes instantaneous removal of soil, the results approximate the settlement seen after a bucket has removed soil along a trench, where the soil is homogenous, dry, and uncompacted. Sarata has used a very similar



(a) (b)

Figure 4 Settlement of the banks of a trench using a modified version of Puhl's method. (a) before settlement (b) after settlement to a critical equilibrium. The angle of repose of the walls is 30 degrees. The surface consists of 10,000 facets. This example required approximately 15 seconds of computation on a Sparc 10 workstation.

method to predict the shape of pile of dry, granular ore as a result of a scooping action [Sarata 94]. Pile shape is modeled well enough that it is also possible to predict the amount of soil scooped to within a few percent.

Li and Moshell have developed a simulation of soil movement that uses the theory of slope settlement to model soil slippage [Li 92]. Relaxation is based on calculation of forces acting on small soil sections through a method closely related to the finite element scheme. They have also extended their analysis of soil settlement for simple soil-tool interaction. However, their model ignores some important phenomena. Since the main criterion for their models is visual impression rather than numerical accuracy, no comparisons have been made to groundtruth, A larger literature exists on the estimation of resistive forces that act on a tool as it moves through the soil. A group of researchers has attempted to estimate cutting resistance based on empirical results for various types of earthmoving machines [Alekseeva 85, Zelenin 86, Nedoredzov 92]. Various indices are suggested based on the configuration of these machines and resistive forces can be roughly estimated by numerically integrating simple equations. Since this work was intended provide analytical tools for machine design, it is not clear how to extrapolate to arbitrary mechanisms and soil conditions, especially in the context of automated machines.

Another body of work, in contrast, attempts to estimate cutting forces based on first principle mechanics. Motivated largely by the need to estimate the forces experienced by tools used to perform tillage, the seminal ideas in this work come from the civil engineer's load-bearing equations for foundations [Terzaghi 47]. These models were extended by several researchers who recognized the similarity to the case of a blade moving through soil [Reece 64, Siemens 65, Luth 65, Hettiaratchi 67, Gill 68]. These researchers have added provisions to account for a variety of tool geometries and orientations. The resultant models use parameters of soil-soil friction, soil-tool friction, soil density, tool depth and tool orientation to obtain order of magnitude predictions of the resistive forces developed in the use of agricultural tools. For example, Figure 5 shows a static analysis of the forces on a tool moving through the terrain. Forces required to accelerate the soil are ignored.

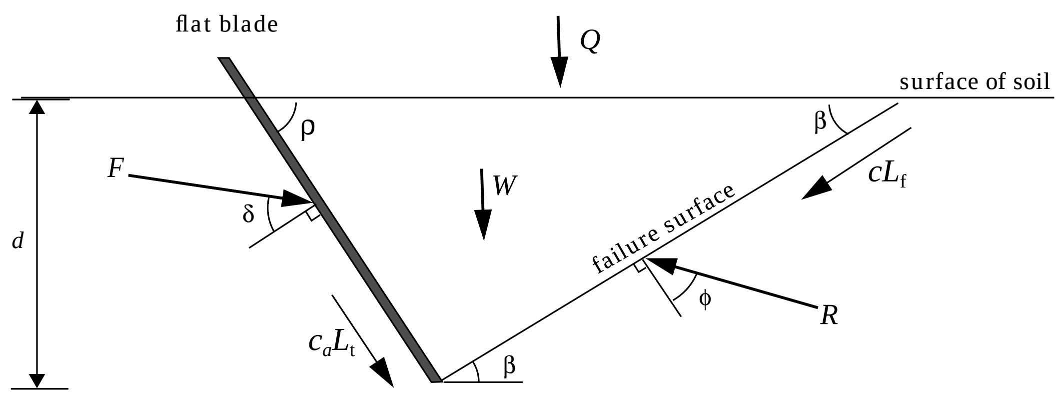


Figure 5 Static equilibrium analysis of a flat blade moving through soil. L_f is the length of the failure surface, L_t is the length of the tool, Q is the surcharge on the wedge, R is the resistance to shearing and W is the weight of the soil wedge. The soil is modeled using a Mohr-Coulomb model that characterizes soil strength as a combination of internal angle of friction (ϕ) and cohesion (c). After figure in [McKeys85].

Recent work has explicitly modeled the mechanics of a bucket moving through terrain. Hemami has proposed a generalized analysis of scooping [Hemami 94]. The paper discusses the forces and how they vary during scooping. Bisse et al. have suggested an analysis to evaluate the sum of the forces and energy involved in making a wheel loader bucket follow an arbitrary trajectory in a muck pile [Bisse 95]. A necessary assumption in both the work of Hemami and Bisse is that the shape of the pile being excavated and the soil properties are known in advance. Malaguti has proposed an analysis of soil-tool interaction based on physical models [Malaguti 94]. The resistive force is composed of the soil-cutting force, the soil-penetration force, and the filling force. These forces are described in an universal earthmoving equation that accounts for the soil's friction and cohesion. Quasi-static and dynamic models of soil-tool interaction (impedance) are also described.

Since soil conditions can vary immensely, prediction of resistive forces will suffer in accuracy if nominal values for soil and soil-tool parameters are used. Estimating forces precisely requires experimentally determined values. Several instruments are available for this process in a laboratory setting [McKyes 85], although in situ testing will obviously provide better results [Wroth 84]. Wadhwa recognized that a better prediction of resistive force might be obtained for a tillage tool when the soil parameters are estimated using a scaled version of the tool itself, rather than using other devices [Wadhwa 80]. Similarly, other researchers have suggested active use of a robot to determine the nature of material the robot is to interact with [Homma 92]. For like reasons, Singh has proposed a method that learns to predict resistive forces based on force measurements during digging with a excavator backhoe bucket [Singh 95b]. The model incorporates parameters motivated by the analysis due to Reece, but the parameters can be non linearly related to the output. This method can capture second order effects that are ignored in the analysis, such as forces due to the compression of the soil in the bucket.

4 Survey of Systems

So far we have examined sensing technologies and models related to automation of earthmoving. Next, we look at methods and systems proposed to perform various earthmoving tasks and classify the systems (or in the case of proposed systems, the fundamental ideas) in levels of increasing autonomy. At the lowest level are tele-operated machines. The operator is removed from the machine but is still required to control the joints much in the same manner as a manually operated machine. Pure tele-operation requires a human to prescribe not only how to dig but also where to dig. At a higher level are systems that perform the job of earthmoving within a narrow range of parameters. In some cases, the task is to servo to some nominal path, while in other cases, the digging trajectory is a result of response to some form of force feedback. Such a machine must be able to deal with varying soil conditions— if the soil is stiffer than expected, for example, the machine should alter its trajectory so as to avoid stalling the actuators. At the next level are systems that abstract the digging process into a coarser specification. Here the system decides where to dig and in some cases a nominal plan of how to dig that can expanded used by lower levels of the autonomous system to be effective. The main idea is that the "better" the plan, the more likely the machine is to execute it. At the highest level is strategic or site planning where the task of performing an entire excavation, such as digging a foundation, is broken down into set of subgoals.

4.1 Tele-operation

Many construction equipment manufacturers now sell tele-operated versions of excavators such as the machine shown in Figure 6. In most cases, the excavator is controlled by

Figure 6 Tele-operated excavator manufactured by Caterpillar Corporation (EL200B). The unit has an operating range of 5000 ft by radio transmission. The joints and tracks are controlled by levers on a remote control panel. Two cameras are mounted on the exterior providing a view of the work site. A third camera is mounted in the cab to view gauges.

levers on a remote control panel resembling those found in the cab. In some cases the operator controls a “master,” a scaled down replica of the excavator which itself behaves like a “slave”. The advantage of using a “master-slave” system is that the control of the excavator is more intuitive. Instead of controlling the joints individually, the operator controls the excavator bucket directly.

Wohlford et al. describe a backhoe that has been tele-operated for dealing with buried hazardous wastes [Wohlford90]. The authors describe the evolution and specification of a remotely controlled excavator that is specifically designed to function productively while its operator is located at a safe distance. Similarly, Burks et al. describe a modified tracked excavator that has been developed to deal with buried waste [Burks 92, Thompson 95]. Their tele-operated military vehicle is equipped with a backhoe and front loader for explosive ordnance disposal and general utility excavation. The system is operated from a hand controller at a remotely located, portable, base station. Nease describes an Air Force program at the Tyndall Air Force base in Florida that has automated an excavator for the purposes of tele-operated repair and maintenance of runways [Nease 92]. Currently, the Tyndall program is focused on exhuming buried ordnance. Operations are conducted on a tele-operated machine noteworthy because it was designed solely to be controlled by a computer as opposed other automated machines that are retrofits of standard construction equipment.

Kojima et al. have described a tele-operated backhoe used to dig deep foundations [Kojima 90]. The operator uses a video monitor while operating a master control mechanism. Nakano et al. have demonstrated a prototype controller for a backhoe excavator that allows an operation to control the bucket in cartesian coordinates, and, to perform slope control [Nakano 92]. In this case, the controls are able to directly specify motion of the bucket rather than of the joints. Recognizing that force information plays an important role in the control of an excavator, some attention has been focused on force-reflecting master-slave systems. Ostaja-Starzewski and Skibiniewski have proposed a method to provide force feedback for an operator controlling an excavator using a kinematically equivalent master controlling the excavator position and providing joint-level force feedback [Ostaja 89]. In contrast, researchers at the University of British Columbia have proposed a system that provides force-feedback in rate mode using a 6 DOF magnetically levitated hand controller [Parker 93, Lawrence 95]. The UBC system uses a dynamical model of the excavator to control the joints such that a smooth trajectory is produced at the bucket. Kraft TeleRobotics Inc. now sells a tele-operated excavator with a force reflecting master [Kraft 90]. With such a device, the operator is able to feel the stiffness of the soil encountered by the bucket in the joints of the master manipulator.

4.2 Trajectory Control

Beyond having to deal with a mechanism with significant inertial properties, the additional complication in the control of an excavator is that the interaction forces during contact with the terrain can be significant. Simple trajectory control almost never suffices unless the mechanism can completely overpower the resistance during digging. Hence, most methods that control the bucket during earthmoving operations are coupled to force or position feedback. However, a variety of schemes have been proposed to map the feedback into actuation, essentially encoding *how* to dig or move to a dump point.

The simplest systems are triggered by pre-set force thresholds. For example, Gocho et al. describe the automation of a wheel loader working in an asphalt plant [Gocho 92]. The wheel loader navigates by following buried underground wires between loading and dumping points. Loading is accomplished by dropping the bucket to the ground and driving into a pile of granular material until a threshold is reached in the hydraulic back-pressure. At this point, the loader curls the bucket and moves to the dumping point.

In a similar vein, Bullock demonstrated a simple scheme to deal with the stiffness of soil [Bullock 89, Bullock 92]. He instrumented a small, four degree-of-freedom manipulator arm with strain gauges on one of the limbs. These strain gauges were monitored while a scoop attached to the end of the manipulator was pushed through the soil along a prescribed path. When the strain measurement exceeded a preset threshold, the scoop was backed up and a "scooping" operation was performed. Huang and Bernold have extended this type of control to deal with very stiff inclusions such as rocks in the soil being excavated [Huang 93]. They use a scaled model of a backhoe that has been outfitted with a load cell between the bucket and the backhoe "stick". An obstacle is indicated by a high reading on the load cell. When this happens, the bucket lifts up by a preset distance and continues parallel to the planned path.

Another type of control scheme uses symbolic rules to choose between control actions. For example, researchers at the University of Lancaster, England have developed an automated excavator (LUCIE) that uses a rule based method to dig trenches [Seward 88, Seward 92, Bradley 93]. Digging is broken down into three phases— penetrate, drag and empty. The excavator is designed to follow a predetermined path but also has rules that allow it react to conditions during the excavation.

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if (penetration depth > 300 mm) then rotate bucket
if (xerror > 70) then y velocity = -2
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An interesting aspect of this system is that it uses the servo error as a measure of the soil resistance as evidenced by the second rule. The authors report that their system has proven capable of autonomously digging a trench to a controlled depth in a variety of ground conditions. More recently the group at Lancaster has ported their development to a commercial mini excavator. Additionally, they are investigating safety sensors that can detect the presence of humans in the vicinity of the excavator using a scanning laser [Seward 96].

Sakai and Cho have simulated excavation using a finite-state machine [Sakai 88]. They show how cylinder pressure and bucket velocity can be used to determine the phase in the digging cycle of the backhoe. A few rules are used to trigger moving from one state to another and, in effect, cause changes in the trajectory of the excavator bucket. Lever et al. at the University of Arizona have implemented a fuzzy-logic based system [Lever 94]. They have used a wrist force-torque sensor and a small shovel mounted on a Puma manipulator to demonstrate digging through sand. Instead of looking at the velocities of the links, their system uses the forces and torques observed during digging. Four rules based on force-torque readings are used to select one of six actions— *lift out*, *up-forward-small*, *up-forward-large*, *down-forward-small*, *down-forward-medium* and *down-forward-large*. Recent work has focused on excavating around stiff inclusions such as rocks. A method similar to that used by Bullock is used to respond to inclusions [Shi 96].

A variant on the rule based schemes described above is to specify control of each degree of actuation based on an intuitive understanding of task. Instead of explicitly specifying the trajectory that the excavator bucket must follow, each joint of an excavator is programmed to react to relevant observations. The path that the bucket follows then emerges from these rules. For example, Sameshima and Tozawa have implemented a fuzzy logic controller to control the process of excavation that is motivated by observations of human operators performing the same task [Sameshima 92]. The operator places the bucket at a starting location. Starting from this position, three rules (Figure 7) are evaluated at every control cycle to determine the velocities of the boom, stick, and bucket joints. The velocities commanded are

	Observations		Actions		
	Bucket Vel	Stick Vel	Bucket Vel	Stick Vel	Boom Vel
RULE 1	L	L	B	B	M
	L	H	B	M	S
	H	L	S	M	S
	H	H	S	B	Z
RULE 2	Bucket Angle		Bucket Vel	Stick Vel	Boom Vel
	L		B	S	S
	H		S	B	Z
RULE 3	Depth of bucket				Boom Vel
	L				Z
	H				S

Figure 7 Fuzzy Rules used by Sameshima and Tozawa.

dependent on the velocities of the bucket and stick at the previous control cycle, the bucket angle, and the depth of the bucket below the ground surface. The observations are classified as binary values (either low or high) and the outputs velocities are discretized into four steps (zero, small, medium and big). The authors suggest a weighting scheme to combine the output of the three rules but it is unclear how the gains are adjusted for excavation in a particular soil. For example, one of the conditions says that if the bucket and the stick are moving slowly (ostensibly because the soil is stiff), then the boom should be raised quickly (thus allowing digging at a shallower depth). If the bucket and stick move at a high speed, then the soil is deduced to be soft and the boom is kept still, allowing a deeper cut. This sort of system might be well suited to mass excavation since it doesn't offer any way to dig a particular shape. This particular system is also noteworthy in that it implements shared control between the operator and the machine. The operator makes high level decisions, such as selecting the starting location of the excavator bucket. After this the robot excavator takes over and completes the rest of the dig. Similar methods of digging using a wheel loader and backhoe are described by Rocke [Rocke 94, Rocke 95]. These systems use pressure sensors inside the cylinders to trigger joint motions based on preset thresholds. The thresholds are parameterized by a scalar that represents soil condition but are fixed otherwise. In the same vein is a controller proposed by Kakuzen et al. [Kakuzen 88]. They have developed a feedback and feed-forward controller for crowd control and level luffing of a crane.

Recently, Rowe and Stentz, at Carnegie Mellon University, have described a method to parameterize the motion of an excavator during a “bench loading” cycle as shown in Figure 8 [Rowe 97]. In a typical excavation a loading machine digs material from a face and dumps

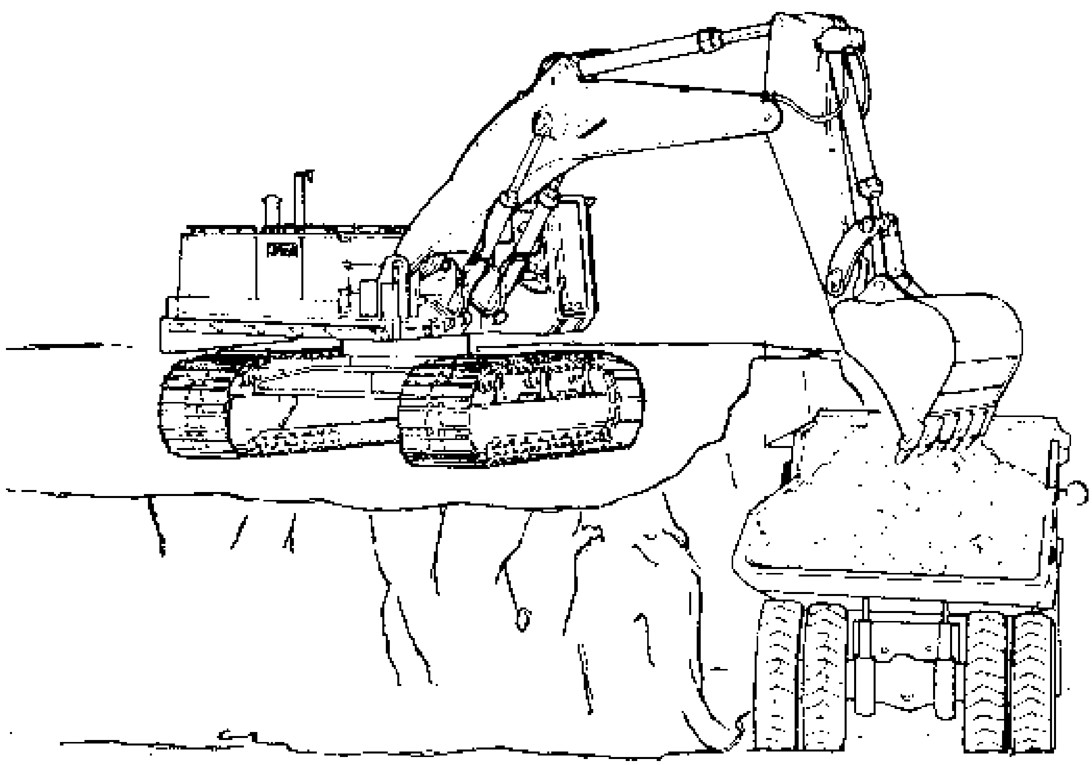

Figure 8 Bench Loading using an excavator backhoe. An onboard rangefinder is used to perceive the shape of the bench and the location of the truck.

the material in a truck, often with a throughput of hundreds of trucks per day. Hence even a few seconds saved in every loading cycle can result in significant improvement in productivity. The authors propose a “template” that encodes the skill of an expert operator performing the task of moving the bucket from the dig face to the truck. Template parameters are computed to fit the specifics of a loading scenario based location of the truck (as perceived from an onboard rangefinder) and kinematic and dynamical models of the excavator. Selection of the digging point, motion during digging and selection of the dumping point are handled separately by other processes. Performance of this system over a short sequence of digging cycles has been demonstrated to be at par with performance of a human operator.

In contrast to some of the heuristic schemes discussed above, Salcudean et al. have proposed a position-based impedance controller for the motion an excavator backhoe during digging [Salcudean 97]. In this approach, the bucket is modeled as a position source and the contact force measured through pressure sensors in the cylinders is used to modify the trajectory.

4.3 Tactical Planning

At the next level of autonomy, it is necessary to determine *where* to dig. In some cases, the a nominal path is also suggested with the idea that the more feasible the path, the more likely it is to be executed faithfully. Koivo suggests a geometric method to plan trajectories for the tip of an excavator bucket when the ground plane can be assumed to be level [Koivo 92]. The depth of a cut is adjusted so that the swept volume fills the bucket. A similar motivation is used by several others to compute the trajectory of a wheel loader bucket digging in a muck pile, where the profile of the pile is known a priori [Bisse 94, Hemami 92b, Hemami 94, Sarata 93]. Sarata's method selects a path in the ore pile consisting of straight lines such that the swept volume is equal to the capacity of the bucket. Hemami's and Bisse's methods find curves that not only satisfy the volume of the bucket but are also optimal in some way. For example, Bisse's method finds a curve that satisfies boundary conditions, achieves a given volume and minimizes the path length to be followed by the bucket. It is assumed that the energy required is directly proportional to the length of the path of the cutting edge.

Takahashi has demonstrated a scaled model wheel loader that uses a camera to determine the place to start digging in the rock pile [Takahashi 94a, Takahashi 95a, Takahashi 95b]. A contour of the rock pile is extracted from the images and candidate digging locations and directions that fill the bucket completely, are chosen. Feng et al. have performed simulation studies to plan the trajectory of an excavator [Feng 92]. They have proposed a method to select between parameterized digs. The authors also use a heuristic rule based system to deal with force overload at the bucket.

In a similar vein is work reported by Singh [Singh 95a] at Carnegie Mellon University. Excavation is posed as a problem of constrained optimization over the space of prototypical, one-step excavating plans. The system uses geometric and force constraints and an objective function (e.g. minimum torque) to produce digging plans. Planning is thus reduced to finding a subset of plans that meet the constraints and optimize an appropriate performance measure. To reason about resistive forces encountered while digging, a method was developed that learns to predict resistive forces encountered during excavation. Given a geometric specification of desired terrain, a kinematic model of the excavator, means of sensing terrain topology, and force data from previous excavation in similar soil, this system excavates trenches to predictable tolerances. This system uses an imaging sensor (laser rangefinder) to perceive the shape of the terrain being excavated (Figure 9). The shape of the terrain is fed back to the excavation planner after every dig.

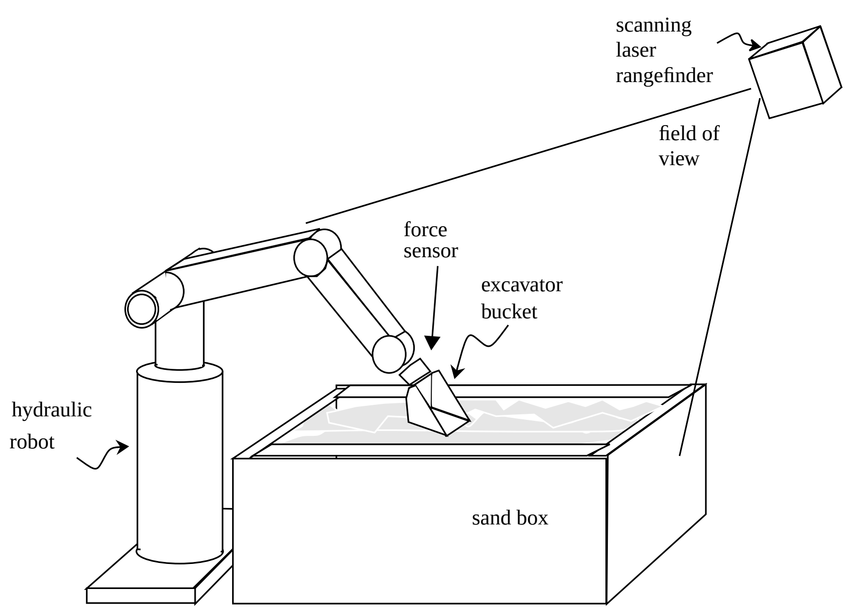

Figure 9 Excavation testbed used by Singh. A laser rangefinder is used to build topological maps of the terrain, such as shown in Figure 3, before each dig. The force sensor is used to build expectation of contact forces during excavation.

4.4 Strategic or Site Planning

At the highest level of abstraction, the task can be stated as such: Given a robot excavator and dimensions of a desired excavation, select a sequence of actions to produce the overall desired shape. Romero-Lois and Hendrickson describe a system that they have implemented to address this issue [Romero-Lois 89]. They customized an expert system

(PLANEX) to plan the sequence of moves of a robotic power shovel equipped with sensors to determine the shape of the terrain and its own position. The planner operates purely on a geometric basis without consideration of the strength of the soil versus the forces that can be developed by the excavator. Similarly, although at a smaller scale, Bullock and Apte describe the generation of subgoals for an excavator [Bullock 90]. The task is essentially to decompose a target volume into smaller volumes that can be tackled by an excavator. Both works described above relied only on simulation studies, and hence the resolution of the subgoals generated by a strategic planner for excavation remains an open question.

We might ask how a broader class of resources (excavating machines and hauling vehicles) may be best allocated to perform the overall task at a construction site. Bernold suggests methods that could be used to schedule a fleet of excavators and haulage vehicles to perform the task of excavation most efficiently [Bernold 86].

4.5 Other Systems

Several other systems do not fit into the above classification. Whittaker et al. demonstrated a novel system that uncovered buried pipes using a vacuum tool mounted on a backhoe arm [Whittaker 85]. Alternately, thin layers of soil are removed, and elevation maps of the terrain are constructed using ultrasonic sensors. Edge detection is performed on the elevation map and pipes are indicated when parallel lines separated by four to ten inches are found. Once a pipe is located, the vacuum tool follows the boundaries of the pipe until the pipe is completely exposed.

Brooks et al. have proposed that the task of planetary excavation might be performed more effectively by many, simple, small autonomous robots, rather than a single, large, complex robot [Brooks 90]. They propose a system which would consist of 20 small bulldozers which work without explicit coordination or communication, but nevertheless cooperate to achieve tasks useful in a lunar construction site. However, no results exist for this type of system.

Hoffman and Simmons describe a simulation system that incorporates a geometric model of the excavator and terrain, a laser scanner model that provides 3-D terrain data and a communication layer that interfaces to external modules [Hoffman 94]. The simulator is designed such that it can completely mimic an excavator and on-board sensors and provides a platform for testing task-level software and for verifying correctness of the system integration. In a somewhat related vein, researchers at the Virtual Environments group at the University of Illinois have created a simulator intended for human users. A user sits in a mock cab of a wheel loader and is able to drive a virtual wheel loader through a scene that is viewed on three walls and the floor using high resolution graphics. The simulated wheel loader can be made to scoop a gravel pile and dump into a truck [Lehner 95]. The real-time soil model conserves volume using a simplified version of the soil models suggested by Li [Li 92].The main purpose of the simulator is to assist in the prototyping of new designs of earthmovers. An associated project allows engineers at various sites to work together on designs of earthmoving machines using distributed virtual reality [Lehner 97].

Recently, a commercial excavator (Caterpillar 416 backhoe-front loader) has been retrofitted for autonomous operation at Carnegie Mellon. The intention is to use this excavator to assist in the remediation of unexploded ordnance. Currently, remediation is performed based on a prior map generated by sub-surface sensors. Working from such maps poses problems in registration and precision especially if the buried objects are deep. The proposed system will verify location of the target during the course of excavation using Ground Penetrating Radar (GPR). A sense-dig cycle is shown in Figure 10. [Herman 94] discusses methods to sense buried objects such as buried pipes and buried ordnance. [Herman 95] discusses results of a robotic system that used GPR to help in automatically unearth a buried object.

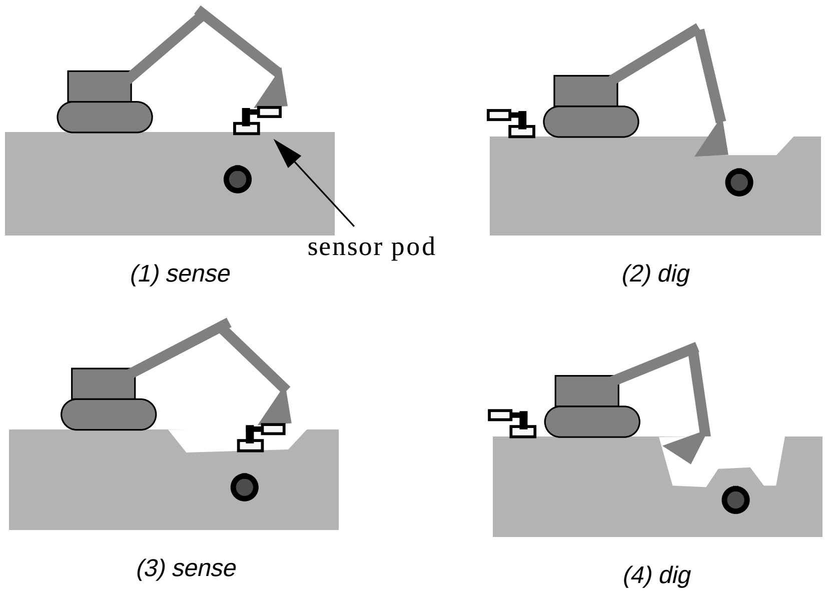

Figure 10 An illustration of the sense and dig cycle to uncover buried ordnance or utilities.

References

[Alekseeva 85] Alekseeva, T. V. and Artem'ev, K. A. and Bromberg, A. A. and Voitsekhovskii, R. I. and Ul'yanov, N.A., *Machines for Earthmoving Work, Theory and Calculations,*. A. A. Balkema, Rotterdam, 1985.

[Bernold 86] Bernold, L. E., Low Level Artificial Intelligence and Computer Simulation to Plan and Control Earthmoving Operations. In *Proc. ASCE Speciality conference on Earthmoving and Heavy Equipment*. Tempe, AZ, 1986.

[Bernold 89] Proceedings of One Day Seminar on Planetary Excavation, Editor Bernold, L. E., University of Maryland Engineering Design Research Center, 1989.

[Bernold 91] Bernold, L., Experimental Studies on Mechanics of Lunar Excavation. *ACSE Journal of Aerospace Engineering*. 4(1), January, 1991.

[Bernold 93] Bernold, L., Motion and Path Control for Robotic Excavation. *ASCE Journal of Aerospace Engineering*. 6(1), January, 1993.

[Bisse 94] E. Bisse, A. Hemami, and E.K. Boukas. Optimal excavation path planning for scooping by a bucket. In *Proc. 6th Canadian Symposium on Mining Automation*, Montreal, QC CANADA, October 1994.

[Bisse 95] E. Bisse, A. Hemami and E. K. Boukas, A comparison of the required energy in loading for four scooping strategies. In *Proc. 3th International Symposium on Mine Mechanization and Automation*, Golden Colorado., Golden, Colorado USA, 1995.

[Boles 90] Boles, W. W., *Lunar Base Construction*. Ph.D. thesis, University of Texas at Austin, December, 1990.

[Bradley 93] Bradley, D.A. and Seward, D.W. and Mann, J.E. and Goodwin, M.R., Artificial intelligence in the control and operation of construction plant-the autonomous robot excavator. *Automation in Construction*. 2(3), 1993.

[Brooks90] Brooks, R.A. and Maes, P. and Mataric, M.J. and More, G., Lunar base construction robots, *In Proc. IROS '90. IEEE International Workshop on Intelligent Robots and Systems*, Jul 1990.

[Bullock 89] Bullock, Darcy M. and Oppenheim, Irving J., A Laboratory Study of Force-Cognitive Excavation. In Proc. *Sixth International Symposium on Automation and Robotics in Construction*. June, 1989.

[Bullock 90] Bullock, D. M. and Apte, S. and Oppenheim, I. J., Force and Geometry Constraints in Robot Excavation. In Proc. *Space 90: Engineering, Construction and Operations in Space*. ASCE, Albuquerque, 1990.

[Bullock 92] Bullock, D. M. and Oppenheim, I. J., Object Oriented Programming in Robotics Research for Excavation. *Journal of Computing in Civil Engineering*. 6(3), July, 1992.

[Burks 92] Burks, B.L. and Killough, S.M. and Thompson, D.H., Remote excavation using the telerobotic small emplacement excavator. *1992 Winter Meeting. International Conference on Fifty Years of Controlled Nuclear Chain Reaction: Past, Present and Future*, pages 559-60. American Nuclear Society, November, 1992.

[Corke 97a] Peter Corke, Jonathan Roberts, Graeme Winstanley, Sensors and Control for Mining Robotics, In *Proc. Fourth International Symposium on Mine Mechanisation and Automatio*n, Brisbane, Australia, 6-9 July 1997.

[Corke 97b] Corke, P. I., Winstanley, G. J., Roberts, J. M., Dragline modeling and control, In *Proc. IEEE Conference on Robotics and Automation*, 1997.

[Cundall 88a] Cundall, P., Numerical experiments on localization in frictional materials. In *Proc. of the workshop on limit analysis and bifurcation theory.* University of Karlsruhe, February, 1988.

[Cundall 88b] Cundall, P. and Board, M. A microcomputer program for modeling large strain plasticity problems. *Numerical methods in geomechanics*. Balkema, Rotterdam, 1988.

[Everett 95] Everett, H. R., *Sensors for Mobile Robots: Theory and Application*, A. K. Peters, Ltd, Wellselly, Massachusetts, 1995

[Feng 92] Feng, P. and Yang, Y. and Qi, Z. and Sun, S., Research on Control Method of Planning Level for Excavation Robot. In *Proc. 9th International Symposium on Automation and Robotics in Construction*. Tokyo, 1992.

[Gill 68] Gill, W. R. and Vanden Berg, G. E., *Agriculture Handbook*. Number 316: *Soil Dynamics in Tillage and Traction.* US Department of Agriculture, 1968.

[Gocho 92] Gocho, T. and Yamabe, N. and Hamaguchi, T. Automatic Wheel Loader in Asphalt Plant. In Proc. *the 9th International Symposium on Automation and Construction*. Tokyo, June, 1992.

[Hemami 92a] Hemami, A. and Daneshmend, L. Force Analysis for Automation of the Loading Operation in an L-H-D Loader. In *Proc. of the IEEE Conference on Robotics and Automation*. Nice, France, May, 1992.

[Hemami 92b] Hemami, H., Study of Bucket Trajectory in Automatic Scooping with LHD Loaders, In *Transactions Institution Mining, Metallurgy*, section A, 102, 1992.

[Hemami 94] H. Hemami. Modeling, analysis, and preliminary studies for automatic scooping. *Advanced Robotics*, pages 1--19, 1994.

[Herman94] Herman, H. and Stentz, A, Active surface/subsurface perception for autonomous excavation, In *Proc. of SPIE Conference*,1994.

[Herman95] Herman, H. and Singh, S., First Results in the Automatic Retrieval of Buried Objects, *Automation of Construction*, Elsevier, 1995.

[Hettiaratchi 67] Hettiaratchi, D. R. P. and Reece, A. R. Symmetrical Three Dimensional Soil Failure. *Geotechnique.* 4(3), 1967.

[Hoffman 92] Hoffman, R., and Krotkov, E., “Terrain Mapping for Long Duration Autonomous Walking”, In *Proc. IEEE/RSJ International. Conference on Intelligent Robots and Systems,* Raleigh, 1992.

[Hoffman 94] Hoffman, R. and Simmons, R., Simulation of Autonomous Robotic Excavation, In *Proc. Robotics for Challenging Environments.* Albuquerque, 1994.

[Homma 90] Homma, K. and Nakamura, T. and Arai, T. and Adachi, H. Spatial image model for manipulation of shape variable objects and application to excavation. In *Proc. IEEE International Workshop on Intelligent Robots and Systems.* 1990.

[Homma 92] Homma, K. and Arai, T. and Adachi, H., Soil Model for Automated Excavation Using Touch Sensed Data. In *Proc. 2nd International Symposium on Measurement and Control in Robotics*. November, 1992.

[Huang 93] Huang, X. D. and Bernold, L. E., Robotic Rock Handling during Backhoe Excavation. *Automation and Robotics in Construction*. 1993.

[Huang 94] Huang, X. D. and Bernold, L. E., Control Model for Robotic Backhoe Excavation and Obstacle Handling. In *Proc. Robotics for Challenging Environments*. Albuquerque, 1994.

[Kakuzen 88] Kakuzen, M. and Hirokazu, A. and Kimura, N., Automatic Control Systems for Construction Machinery. In *Proc. 5th International Symposium on Robotics in Construction*. Tokyo, 1988.

[Koivo 92] Koivo, A. J., Controlling an Intelligent Excavator for Autonomous Digging in Difficult Ground. In *Proc. the 9th International Symposium on Automation and Construction*. Tokyo, June, 1992.

[Kojima 90] Kojima, Y. and Fukuda, J. and Kuramoto, S. and Sano, Y. and Akiba, N., Remote Control Type Excavating Robot for Deep Foundation. *Fujikura Technical Review*. 1990.

[Kraft 90] Force Feedback Excavator and Material Handling System. Kraft TeleRobotics Inc. Overland Park, Kansas, 1990.

[Labonte 94] Labonte, F. and Cohen, P., Perceptual aspects of mining equipment teleoperation. In *Proc. 6th Canadian Symposium on Mining Automation*, pages 179--188, Montreal, Canada, October 1994.

[Lawrence 95] Lawrence, P. D., S.E. Salcudean, N. Sepehri, D. Chan, S. Bachmann, N. Parker, M. Zhu and R. Frenette, Coordinated and Force-Feedback Control of Hydraulic Excavators, In *Proc. International Symposium on Experimental Robotics*, July 1995.

[League 96] League, R. B., and Lay, N. K, System and method for Tracking Objects Using a Detection System, US Patent 5587929, 1996.

[Lehner 95] Lehner, V. D., Real-time simulation of soil interaction and stability for an earthmoving equipment prototyping system, Masters thesis, Department of Computer Science, University of Illinois and Urbana-Champaign, 1995.

[Lehner 97] Lehner, V. D., DeFanti, T.A., Distributed virtual reality:supporting remote collaboration in vehicle design, I*EEE Computer Graphics and Applications; IEEE Comput. Graph. Appl*; vol.17,no.2; IEEE; March- April 1997;

[Lever 94] Lever, P. and Wang, F. and Chen, D., Intelligent Excavator Control for a Lunar Mining System. In *Proc. ASCE Conference on Robotics for Challenging Environments*. Albuquerque, February, 1994.

[Li 92] Li, X. and Moshell, J. M., *Physically based models of dynamic terrain in virtual environments*. Technical Report CS-TR-92-27, University of Central Florida, 1992.

[Luth 65] Luth, H. J. and Wismer, R. D., Performance of Plain Soil Cutting Blades in Soil. *Transactions of the American Society of Agricultural Engineers*. 1965.

[Malaguti 94] Malaguti, F., Soil machine interaction in digging and earthmoving automation, In *Proc. of the 11th International Symposium on Automation and Robotics in Construction* (ISARC); Brighton, UK; 24-26 May 1994.

[McKyes 77] McKyes, E. and Ali, O. S., The Cutting of Soil by Narrow Blades, *Journal of Terramechanics*, 14(2), 1977.

[Mckyes 85] McKyes, E. *Soil Cutting and Tillage*. Elsevier, 1985.

[Mulligan 89] Mulligan, I. J., Mackworth, A., Lawrence, P., A model based vision system for manipulator position sensing, In *Proc, International Conference Robotics and Automation*, 1989.

[Nakano 92] Nakano, E., Tsuda, N, Inuoe, K., Kayaba, K., Kimura, H., Matsukawa, Okuda, S., Development of an advanced way of improvement of the maneuverability of a backhoe machine, In *Proc. 9th International Symposium on Automation and Robotics in Construction*, June 1992, Tokyo.

[Nease 93] Nease, A.D.; Alexander, E.F, Air Force construction automation/robotics. In *Proc. 10th International Symposium on Automation and Robotics in Construction (ISARC);* Houston, May 1993.

[Nedoredzov 92] Nedoredzov, I., Forces prediction of underwater soil cutting by excavating robots. *9th International Symposium on Automation and Construction*. Tokyo, June, 1992.

[Ostaja 89] Ostaja-Starzewski, M. and Skibiniewski, M., A Master Slave Manipulator for Excavation and Construction Tasks. *Robotics and Autonomous Systems*. 4 1988/89.

[Parker 93] Parker, N. R, S.E. Salcudean, P.D. Lawrence, Application of Force Feedback to Heavy Duty Hydraulic Machines, In *Proc., International Conference on Robotics and Automation*, Atlanta, Georgia, 1993.

[Peussa 95] Peussa, P., Chan, D., Bachmann, S., Lawrence, P. D., Tafazoli, S., and Salcudean, S. E., Using solenoid valves for proportional pilot pressure control in mini excavators, In *Proc. of the 4th Scandinavian International Conferenc*e, pp. 1139-1151, Tampere, Finland, September 1995.

[Puhl 92] Puhl, H. On the modeling of real sand piles. *Physica A*. 182(3), March, 1992.

[Reece 64] Reece, A. R. The fundamental equation of earth moving mechanics. In *Proc. of Institution of Mechanical Engineers*. 1964.

[Register 90] Register, B., Proceedings of *FY89 Workshop on Extraterrestrial Mining and Construction*. Technical Report LESC-27585, Lyndon B. Johnson Space Center, 1990.

[Rocke 94] Rocke, D. J., Control system for automatically controlling a work implement of an earthmoving machine to capture material, US Patent 5528843, 1994.

[Rocke 95] Rocke, D. J., Automatic excavation control system and method, US Patent 5446980, 1995.

[Romero-Lois 89] Romero-Lois, H. and Hendrickson, C. and Oppenheim, I., A Strategic Planner for Robot Excavation. In *Proc. Sixth International Symposium on Automation and Robotics in Construction*. June, 1989.

[Rowe 97] Rowe, P., and Stentz, A., Parameterized scripts for motion planning, In *Proc. of International Conference on Intelligent Robots and Systems* (IROS), Grenoble, France, 1997.

[Sakai 88] Sakai, T. and Cho, K., Operation System for Hydraulic Excavator for Deep Trench Works. In *Proc. 5th International Symposium on Robotics in Construction*. Tokyo, 1988.

[Salcudean 97] S.E. Salcudean, S. Tafazoli, P.D. Lawrence and I. Chau, Impedance control of a teleoperated mini excavator, In *Proc. of the 8th IEEE International Conference on Advanced Robotics* (ICAR), Monterey, California, July 1997.

[Sameshima 92] Sameshima, M. and Tozawa, S., Development of Auto Digging Controller for Construction Machine by Fuzzy Logic Control. In *Proc. of Conference Japanese Society of Mechanical Engineers*, 1992.

[Sarata 93] Sarata, S., Concept of an autonomous system for piled ore shoveling, In Proceedings of the International Symposium on Mine Mechanization and Automation, June 1993, Lulea, Sweden.

[Sarata 94] Sarata, S., Ore pile model for scooping task planning, Journal of the Mining and Materials Processing Institute of Japan, Vol 110, Number 9, 1994.

[Sarata 95] Sarata, S., Sato, K., and Yuta, S., Motion Control System for Autonomous Wheel Loader Operation, In Proceedings, International Symposium on Mine Mechanization and Automation, June 1995, Golden, Colorado.

[Scheding 97] S. Scheding, G. Dissanayake, E. Nebot, H. Durrant Whyte, Slip Modeling and Aided Inertial Navigation of an LHD, *In Proc. IEEE Conference Robotics and Automation*, 1997.

[Seward 88] Seward, D. and Bradley D. and Brasserie, R., The Development of Research Models for Automatic Excavation. In *Proc. 5th International symposium on Automation and Robotics in Construction*, 1988.

[Seward 92] Seward, D. and Bradley, D. and Mann, J. and Goodwin M., Controlling an Intelligent Excavator for Autonomous Digging in Difficult Ground, In *Proc. 9th International Symposium on Automation and Construction*, June 1992, Tokyo.

[Seward 96] Seward, D. Margrave, F., Sommerville, I, Morrey, R., LUCIE the Robot Excavator- Design for System Safety, in *Proc. IEEE International Conference on Robotics and Automation, Minneapolis,* May 1996.

[Shi 96] X. Shi, Lever, P. and Wang, F., Experimental Robotic Excavation with Fuzzy Logic and Neural Networks, in *Proc. IEEE International Conference on Robotics and Automation,* Minneapolis, April 1996.

[Siemens 65] Siemens J. C. and Weber, J. A. and Thornburgh, T. H., Mechanics of soil as influenced by model tillage tools. *Transactions of the American Society of Agricultural Engineers,* 1965.

[Singh 95a] Singh, S., *Synthesis of Tactical Plans for Robotic Excavation*, Ph.D Thesis, January, 1995, Robotics Institute, Carnegie Mellon University, Pittsburgh, PA 15213.

[Singh 95b] Singh, S., Learning to Predict Resistive Forces During Robotic Excavation, in *Proc. IEEE International Conference on Robotics and Automation,* Nagoya, May 1995.

[Smith 88] Smith, J. R., *Basic Geodesy: An Introduction to the History and Concepts of Modern Geodesy Without Mathematics*, Landmark Enterprises, ISBN: 0910845336, 1988.

[Tafazoli 96] Tafazoli, S., Lawrence, P. D., Salcudean, S. E., Chan, D., Bachmann, S. and. de Silva, C., Parameter Estimation and Friction Analysis for a Mini Excavator, In *Proc. of 1996 IEEE International Conference on Robotics and Automation*, Minneapolis, Minnesota, USA, Apr. 1996.

[Takahashi 94a] Takahashi, H., Kamata, H.; Masuyama, T.; Sarata, S., Concept and model experiments on automatic shoveling of rocks from the rock piles, In *Proc. 16th Annual Conference on Computers and Industrial Engineering*; Ashikaga, Japan;, March 1994.

[Takahashi 94b] Takahashi, H., Tsukamoto, Y., Kamata, H., Masuyama, T., Model analysis on the bucket control for automatic shoveling, In *Proc. 16th International Conference on Computers and Industrial Engineering*, March 1994.

[Takahashi 95a] Takahashi, H., Kamata, H., Masuyama, T., Sarata, S., Autonomous shoveling of rocks by using image vision system on LHD, In *Proc., International Symposium on Mine Mechanization and Automation*, June 1995, Golden, Colorado.

[Takahashi 95b] Takahashi, H., A stereo vision system using multi slit lights for underground vehicle, In P*roc. of Second Asian Conference on Computer Vision*. '95; Part: vol.2; Singapore; 5-8 Dec. 1995; Singapore.

[Teach 93] Teach, T., Earthmoving apparatus and method for grading land providing continuous resurveying, US Patent 5375663, 1993.

[Terzaghi 47] Terzaghi, K., *Theoretical soil mechanics*. Wiley, New York, 1947.

[Thompson 95] Thompson, D.H.; Killough, S.M.; Burks, B.L.; Draper, J.V., Design of the human computer interface on the telerobotic small emplacement excavator, In *Proc. 1995 Winter Meeting of American Nuclear Society*; San Francisco, CA, USA; 29 Oct.-2 Nov. 1995

[Toups 90] Toups, L. D. and Herrera, A. *Planet Surface Systems Reference Architecture Description for the Lunar/Mars 90 Day Study Period*. Technical Report, Lockheed Engineering and Sciences Company, Inc., 1990.

[Vaha 91a] Vaha, P.K. and Skibiniewski, M. J. and Koivo, A. J., Kinematics and Trajectory Planning for Robotic Excavation. In *Proc. ASCE Construction Congress II*. Cambridge, MA, 1991.

[Vaha 91b] Vaha, P.K. and Skibiniewski, M. J. and Koivo, A. J., Excavator Dynamics and Effect of Soil on Digging, In *Proc. International Symposium on Automation and Robotics in Construction*, Stuttgart, Germany, 1991.

[Vaha 93a] Vaha, P.K. and Skibniewski, M. J., Dynamic Model of An Excavator. *ASCE Journal of Aerospace Engineering*. 6(2), April, 1993.

[Vaha 93b] Vaha, P.K. and Skibniewski, M. J. Cognitive Force Control of Excavators. *ASCE Journal of Aerospace Engineering*. 6(2), April, 1993.

[Wadhwa 80] Wadhwa, D., Force Prediction Equation Using Distorted Model as an Analog Device, *Journal of Terramechanics*, Great Britain, 1980.

[Wells 86] Wells, D., *Guide to GPS Positioning*, Larry d Hothem, ISBN: 0920114733, 1986.

[Whittaker 85] Whittaker, W. and Turkiyyah, G. and Bitz, F. and Balash, J. and Guzikowski, R. and Montgomery, B. and Akdogan, R. First Results in Automated Pipe Excavation. In *Proc. of the Second International Conference on Robotics in Construction*. Pittsburgh, PA, May, 1985.

[Wohlford 90] Wohlford, W.P.and Bode, B.D. and Griswold, F.D. New capability for remotely controlled excavation. In *Proc. 1990 Winter Meeting of the American Nuclear Society*, pages 628-9. American Nuclear Society, November, 1990.

[Wroth 84] Wroth, C. P. The interpretation of insitu soil tests. *Geotechnique.* 34(4), 1984.

[Yong 77] Young, R. and Hanna, A. Finite element analysis of plane soil cutting. *Journal of Terramechanics,* 1977.

[Zelenin 86] Zelenin, A. N. and Balovnev, V. I. and Kerov, L. P. *Machines for moving the earth.* A. A. Balkema, Rotterdam, 1986.