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EXTENDED EARTHMOVING WITH AN AUTONOMOUS EXCAVATOR

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The automation of earthmoving equipment is an endeavor that has the potential for improving the efficiency of the construction and mining industries, removing workers from hazardous situations such as in cleaning up toxic waste, and even enabling extraterrestrial exploration . In a four year program, we have investigated the automation of truck loading with a hydraulic excavator in a mass excavation scenario. As shown in Figure 1, the excavator sits on top of an elevated bench, removes material from the bench, and deposits it into an awaiting truck.

There are several reasons for investigating the automation of truck loading with an excavator. First, it has the possibility of improving productivity. In a mining situation, even a small fraction of improvement in cycle time can add up over an eight hour shift allowing hundreds of tons of additional material to be excavated. It also requires several years of experience for an operator to be able to run the machine at its full potential. Even then, expert operators cannot maintain peak performance levels due to fatigue. Worker safety is another reason for automation. Every year people are injured while working in or around earthmoving machines. This can be alleviated by removing the worker from the machine, and by appropriate placement of sensors for monitoring the work area.

Figure 1: Excavator loading a truck in a mass excavation scenario. The excavator sits on top of an elevated bench, removes the material from the bench, and deposits it into the back of the truck.

In this program known as the Autonomous Loading System (ALS), we have demonstrated the ability to completely automate the task of loading trucks with an excavator. The automated excavator is capable of observing the dig face and deciding where to dig. It can then execute the dig in an efficient manner, and capture the material into the bucket. It is capable of observing and recognizing the truck, localizing its position, and deciding where to dump the material into the truck bed. It can move between the dig and the dump locations in a timely manner while ensuring that it does not hit any obstacles in its path. The system has been demonstrated to accomplish the entire truck loading task at speeds roughly equivalent to an expert human operator. In addition, it has been demonstrated that the system is capable of operating for several hours without any human assistance.

The focus of this thesis is on the development of the system's ability to dig effectively for extended periods of time. This can be broken up into three interrelated problems. The first concern is *how to dig.* We need a method that fills the bucket rapidly, and is robust to unanticipated digging forces. Then there is the problem of *where to dig* so that constraints are not violated and the material is removed from the bench in an optimal fashion. Finally there is the issue of *cleaningup the floor and repositioning the machine* so that excavation can continue after most of the material has been removed. In this thesis, an approach is presented which addresses all three of theseissues. Experimental results are also presented which demonstrate the effectiveness of the digging operations with the automated excavator over an extended number of sequences.

Figure 2: A side view of the Autonomous Loading System (ALS). The ALS system is a commercially available 25 ton excavator that has been outfitted with a suite of sensors and on-board computing for the purpose of automation.

The Autonomous Loading System is a 25 ton commercial excavator that has been modified for thepurposes of automation. Figure 2 shows a side view of the system. An excavator is comprised ofthree planar implements connected through revolute joints known as the boom, stick, and bucket,and one vertical revolute joint known as the swing joint. In addition the excavator has two independently movable tracks. The boom, stick, and bucket are controlled via prismatic hydraulicactuators (also known as hydraulic cylinders) interconnected across the implements, and the swing joint and tracks are controlled with hydraulic motors.

The excavator has been outfitted with electrohydraulic controls, a suite of sensors, and on-board computing. Each implement has a resolver attached to its rotational joint for sensing angular position and velocity. Pressure sensors are located in the hydraulic lines attached to each hydraulic actuator, enabling the measurement of the actuator forces. Two scanning laser range finders are attached at the top of the machine for sensing the surrounding terrain, the truck, and any potential obstacles. All of the decision making processes are conducted on-board the machine with an array of four MIPS processors.

The overall software architecture is shown in Figure 3. The center of the architecture is a motion planning module which is responsible for guiding the machine through all of its motions. This module receives inputs from several perception modules, selects a path of motion, and then executes the motion by sending commands to a machine control interface. The motion planning module is also responsible for dictating the motion of the range sensors so that they are positioned properly during the work cycle. More details about the motion planning module can be found in.

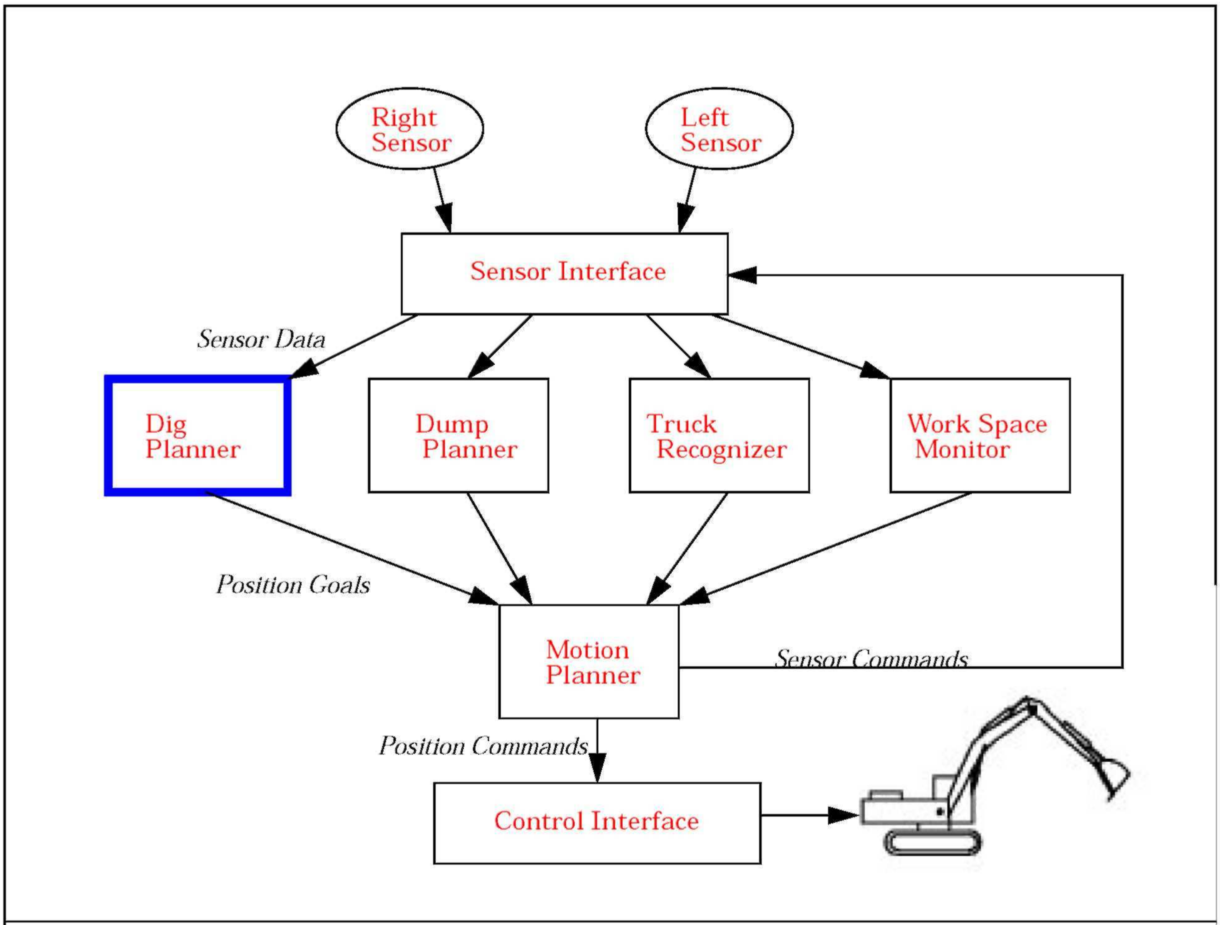

Figure 3: Overall software architecture for the ALS system. A motion planning module is responsible for dictating the motion of the machine. Perception modules are used to select goal points for the excavator based on range sensor information. The hardware interfaces are accomplished through the left and right sensor interfaces and the machine controller interface. The focus of this thesis is on the dig planning module.

The perception modules receive data from the range sensors, and then use this information to accomplish their various tasks. For instance, the truck recognizer module picks out the truck from the range sensor data, and localizes the truck's position. The dump planning module uses the range sensor information to observe the interior of the truck bed and decides where the next bucket of material should be placed. The dig planning module (the focus of this thesis) observes the shape of the terrain, and decides where to dig or where to position the machine so that a suitable dig may be achieved. Finally a work space monitor module uses the range information to look for potential obstacles entering the work area. More information about all of these modules can be found in 8]. The outputs of the perception modules correspond to machine configuration goals for the motion planning module, and the motion planning module plans a path for the excavator based on this information.

Finally, the interface to the hardware is accomplished through three separate modules. A left and right sensor interface receives positioning commands from the motion planning module, and communicates this information to the low level range sensor control hardware. The sensor interface modules are also responsible for receiving the range data from the sensors and sending this information to the perception modules. The machine control interface receives commands from the motion planning module and communicates these commands to the low level machine control hardware. The low level hardware can execute closed loop position commands or open loop joint velocity commands. The machine control interface also receives the state of the machine from the low level hardware (such as joint positions, cylinder pressures, etc.) and communicates this back to any of the modules that need the information.

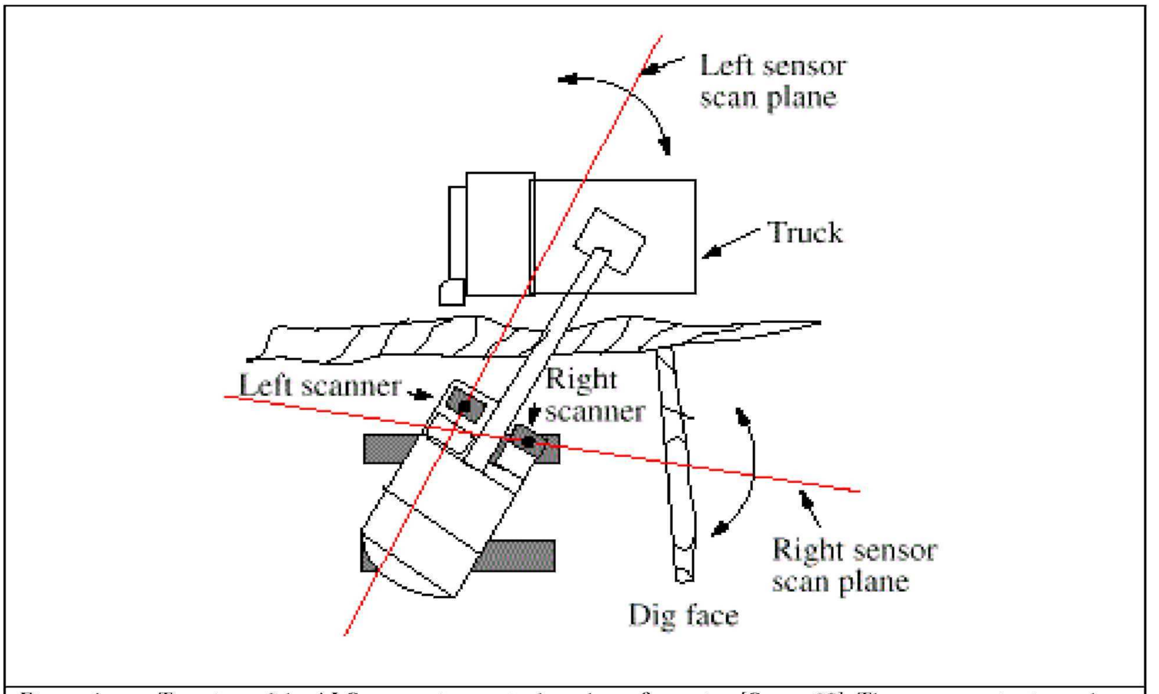

Figure 4: Top view of the ALS system in a typical work configuration [Stentz 98]. The excavator is situated on top of an elevated bench, and the truck is positioned at the base of the bench to the left of the excavator. The orientation of the sensors are shown by the plane of data that is being scanned. The left sensor information is used to decide on the dump location, and the right sensor data is used to select the dig location.

A typical working scenario is shown in Figure 4, and this can be used to describe the work cycle. The excavator is situated on top of an elevated bench and the truck is parked at the base of the bench known as the 'floor', and situated off to one side. The machine removes a bucket of material from the dig face and begins swinging to the truck. As it is swinging towards the truck, the left sensor is positioned so that it can scan the truck, and the right scanner is positioned so that it can scan the dig face. The truck recognizer module uses the data from the left sensor to localize the position of the truck, and the dump planning module decides where to dump the material. The dig planning module uses the data from the right sensor to decide on the next dig location. After the dump maneuver is executed, the machine begins swinging back to the right to the selected dig location. Meanwhile the dump planning module is using the left sensor data to observe the deposited material in the truck to select the next dump location. This process of digging and dumping is continued until the truck is filled, at which point a new truck arrives, and the process starts over.