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THE DEVELOPMENT OF RESEARCH MODELS FOR AUTOMATIC EXCAVATION

Derek Seward
David Bradley
Robert Bracewell

Department of Engineering
University of Lancaster
U.K.

ABSTRACT

Lancaster University has recently begun research into construction robotics and initial concentration is on excavation plant. This paper describes the building of computer and small-scale models to facilitate research and development into hardware and control strategies. The emphasis is on maintaining flexibility to allow the research the widest possible scope. For this reason a modular system for the models was devised so that compatible components can built-up in various ways. A selection of these modules is described.

1. Background

A multi-disciplinary team of civil, electrical and mechanical engineers has recently established construction robotics research at Lancaster. Initially it is the intention of the group to concentrate on the excavation process, and the back-hoe excavator arm provides an excellent vehicle for exploring the required technologies. Existing back-hoe arms have already evolved into efficient structures of robotic form, and there is ample scope for adding intelligence in order to improve speed of operation, accuracy, fuel economy, ease of use and independence from conventional setting-out procedures.

Existing excavator arms weigh about one tonne travel at 3 metres per second and develop ram forces of up to 20 tonnes. Although it is intended to eventually concentrate the work on a real back-hoe, it was decided that for reasons of safety and convenience it is highly desirable to be able to experiment with control strategies firstly on a computer simulation and secondly on a small-scale model where the forces involved have less potential for damage.

In designing the models the emphasis was placed on flexibility and compatibility, and for this reason a modular approach was adopted. A selection of possible modules is shown in Figure 1 and although it may be decided not to proceed with all the modules, the system is designed to keep all options open at the outset.

2. Computer Simulation

In working with the model arm, computer simulations will be used to investigate, develop and establish operational and control strategies which can then be incorporated into the model. Initially, this will require that the general operational environment into which the robot arm is to be introduced should be modelled and the operation of the arm within that environment considered. Once a suitable model of the environment

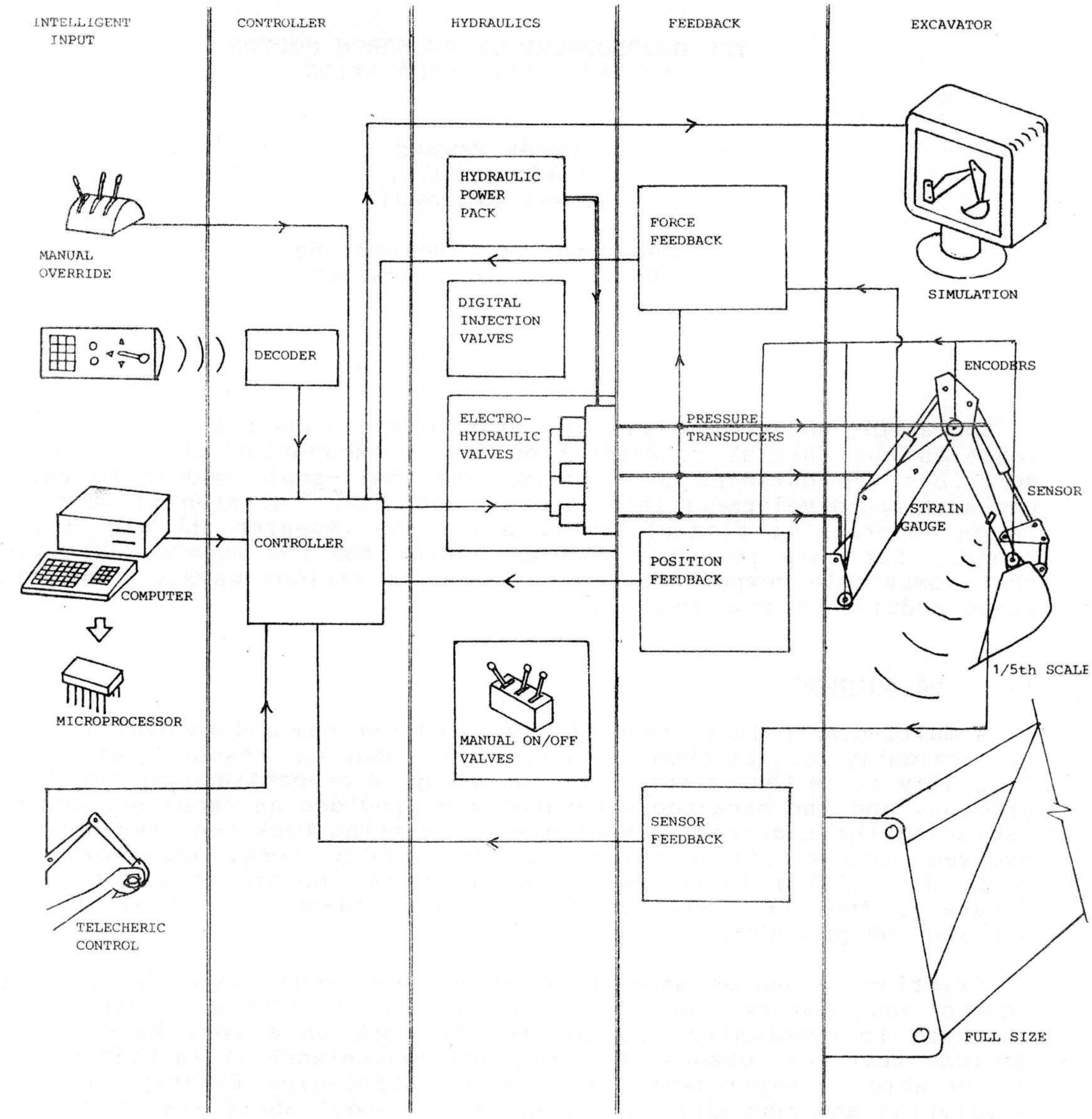

FIGURE 1 Modular Excavator System

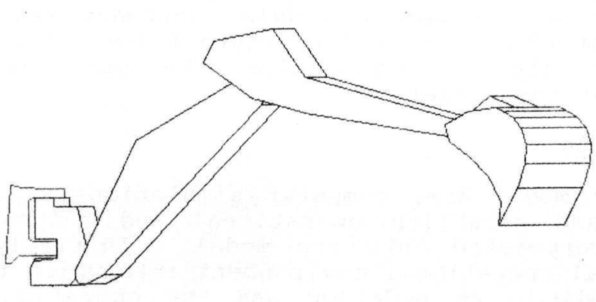

FIGURE 2
Graphical Output
from GRASP

has been achieved a kinematic model, capable of being operated by the same controller and using the same operational and control strategies as are used on the model arm will be required. This second programme will be used both as a means of testing such strategies and of developing the necessary software for use with the model, and ultimately with the full size, arm.

The first of these objectives can be met by using the GRASP package developed at Nottingham University[1]. This package combines the kinematic modelling of the arm as a multi-jointed robot with the solid modelling of both the arm and its environment (figure 2). Once the arm and its environment have been modelled then the operation of the arm within that environment can be simulated. Among the strategies to be investigated in this initial phase are:

* Excavation to a level while remaining under general operator control.
* Incremental dig cycles following a teach sequence by the operator.
* Automatic unload cycles following a learn sequence.

Each of these strategies can be examined using the simulation to determine factors such as approach angles, constraints on joint motion required for various operations, the effect of varying joint acceleration and deceleration rates on cycle times and, using the clash detection routines inherent to GRASP, any possible collisions with other items of plant, such as trucks being used for spoil removal, in the vicinity of the arm. Typical graphical output from GRASP is shown in Figure 2.

Though GRASP can be used to examine the environment in which the arm will be operating it is not able, in the form currently available, to operate in a real time, interactive mode responding to operator commands, nor can it generate the control software required for manipulating the arm independently of an operator. For these objectives a second program, involving a basic kinematic model of the arm will be required. This program can then be interfaced with the same operator controls as will be used on the physical model of the arm to reproduce the same motion sequence. By integrating the information about arm operation obtained from the use of the GRASP package with the program for the basic kinematic model to, for example, modify the operator commands to conform with predefined constraints.

Ultimately, it is envisaged that the kinematic model will be able to provide a mechanism for learning about the way in which operators control a real arm and to incorporate this information into the control system for such an arm.

3. Small Scale Model

The following sections describe each of the modular stages of the system.

3.1 Backhoe Excavator

Fifth scale was adopted for the model as it seemed the best compromise between ease of construction, economy and the ability to perform realistically. Also, it was decided that hydraulics should be reatined as the power source, and fifth scale results in 20 mm diameter hydraulic cylinders, which are about the smallest available for conventional hydraulics. It is important that the model can actually perform as a excavator, and hydraulics is the best way of achieving the necessary power, speed, stroke and robustness, as well as the most realistic appearance. The model is shown in Figures 3 and 4.

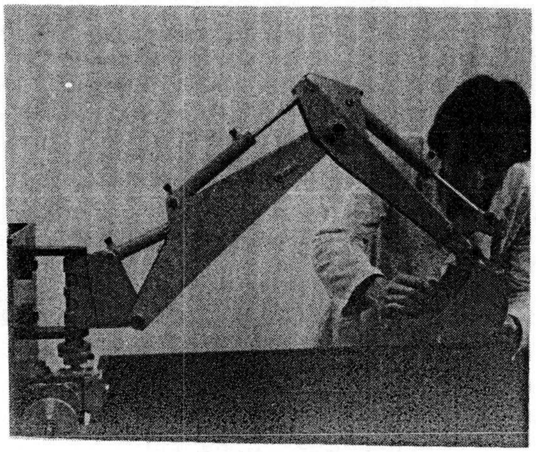

FIGURE 3
1/5th SCALE MODEL

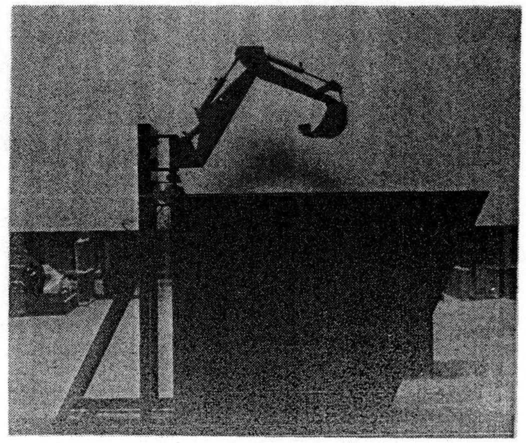

FIGURE 4
SOIL BOX FOR TRIAL EXCAVATIONS

3.1.1 Backhoe Kinematics

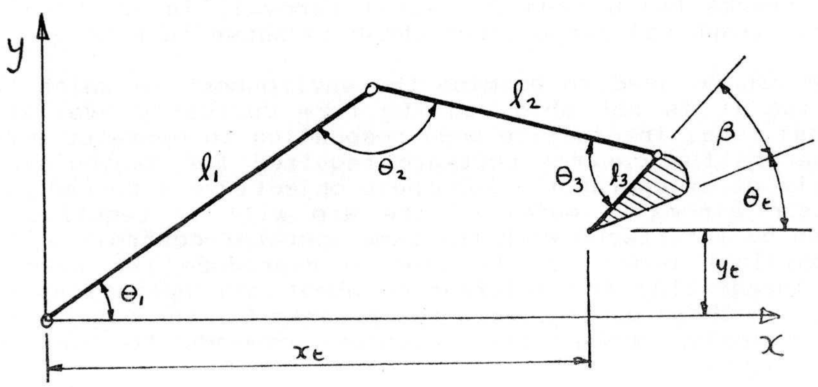

FIGURE 5

When operating in the digging plane a conventional arm has three degrees of freedom θ_1, θ_2 and θ_3 and the requirement is to control the bucket tip positional coordinates and inclination x_t, y_t and θ_t. Because $\theta_2 < 180°$ there is a unique combination of joint angles for a particular value of tip position and inclination.

For robots with more degrees of freedom homogenous transformations tend to be used to find the values of θ_1, θ_2 and θ_3, but in this case it is simpler and more efficient in computing time to use trigonometry.

The forward transformation can easily be seen to be:

$$x_t = \ell_1 \cos\theta_1 - \ell_2 \cos(\theta_1 + \theta_2) + \ell_3 \cos(\theta_1 + \theta_2 + \theta_3) \quad (1)$$

$$y_t = \ell_1 \sin\theta_1 - \ell_2 \sin(\theta_1 + \theta_2) + \ell_3 \sin(\theta_1 + \theta_2 + \theta_3) \quad (2)$$

$$\theta_t = \theta_1 + \theta_2 + \theta_3 + \beta \quad (3)$$

Groover et al[2] show how the much more useful reverse transformation can be obtained.

$$\theta_2 = \mathrm{Cos}^{-1} - \left[\frac{x_3{}^2 + y_3{}^2 - \ell_1{}^2 - \ell_2{}^2}{2\ell_1\ell_2}\right] \qquad (4)$$

$$\text{where} \quad x_3 = x_t + \ell_3 \, \mathrm{Cos}(\theta_t + \beta) \qquad (5)$$

$$y_3 = y_t + \ell_3 \, \mathrm{Sin}(\theta_t + \beta) \qquad (6)$$

$$\theta = \mathrm{Tan}^{-1} \frac{x_3\ell_2\mathrm{Sin}\theta_2 + y_3(\ell_1 - \ell_2\mathrm{Cos}\theta_2)}{x_3(\ell_1 - \ell_2\mathrm{Cos}\theta_2) - y_3(1 - \ell_2\mathrm{Sin}\theta_2)} \qquad (7)$$

$$\theta_3 = \theta_t - \theta_1 - \theta_2 - \beta \qquad (8)$$

for a given path in space the above equations enable the joint angles to be determined.

3.2 Feedback

3.2.1 Positional Feedback

Whatever type of hydraulic valves are used to control the arm it is clear that closed-loop control with positional feedback is required in order to obtain a suitable degree of accuracy. The conventional robotic approach is to use digital-optical encoders on the joints however size and cost preclude them from the model. A simple and cheap method is to use small conductive plastic servo potentiometers linked to analogue-to-digital converters.

A good excavator driver can achieve level accuracy of about 50 mm with a conventional backhoe. We are therefore aiming for 25 mm and substitution into equation (2) with the arm fully extended in the x-direction indicates that joint angles need to be controlled to within 0.2° in order to achieve this accuracy. For the range of movement of the excavator joints this represents about 1000 graduations. Work is currently underway to investigate the linearity of the potentiometers and determine whether or not a 'look-up table' approach is required.

Other types of positional feedback are being considered. Bucket position and inclination is uniquely defined by the position of the piston in the cylinders so some form of linear displacement transducer on the cylinder is a possibility. An attractive option would be to monitor fluid flow into and out of the cylinders. This has the advantage of putting all the sensing into the cab and leaving a completely unmodified excavator arm, but accuracy could be expensive to achieve.

Lastly consideration is being given to direct sensing of the position of the bucket tip by embedding some form of transponder or target into part of the bucket. This means that any wear and tear in the joint bearings would automatically be compensated.

3.2.2 Force-Feedback

Skilled excavator drivers use very different bucket trajectories when digging in soft clay and hard gravel. For intelligent automatic control force-feedback is vital if efficient bucket-filling in varying soils is to be achieved. Force feedback can also be used to produce better feel when using telecheric control and to compensate for bending deformations in the structure if these prove significant.

The obvious method of obtaining force feedback is by means of pressure transducers in the hydraulic pipes but strategic placing of strain gauges on the cylinders or inside the box sections of the arm may be just as effective and much cheaper.

3.2.3 Sensors and Vision

It is anticipated that the first generation of robotic excavators will retain a human driver but that he will be provided with intelligent assistance. A useful feature is the ability to detect hidden services such as electricity cables, telephone cables, and gas and water pipes. A system to provide warning to the driver before the bucket causes damage is regarded as a priority research area.

For more advanced autonomous operation the vehicle needs to be provided with some form of vision system capable of determining both the original ground profile on the digging line and the final excavated level in case material falls in from the sides. A range-finder device is being considered to perform this function.

3.3 Hydraulics

Electro-hydraulic valves are obviously a key component of the system. With closed-loop feedback simple on/off valves could provide adequate control, however much more expensive linear-proportional servo valves will produce smoother and more positive movement with longer sampling intervals. Both types of valve will be experimented with however.

Conventional manual on/off valves are also provided, mainly for comparison purposes.

Because flow rates are considerably greater on the full scale arm different valves will of course be required but the control signals are identical thus maintaining the modular concept.

3.4 Controller and Intelligent Input

It is tempting to adopt a cheap micro-computer system to provide control to the fifth scale model, and although this may be done in the short term to obtain quick results, the major part of the research will use a professional microprocessor development system. Such a system will enable the work to be conducted in a high level language with good debugging capabilities, but the end result will be relatively cheap embedded processors. It is beyond the scope of this paper to go into details of the processing other than to say that an Intel based system is being considered. The modular approach of different functions being provided by separate cards will be maintained so that, for example, additional sensor feedback can be incorporated.

3.5 References

1. GRASP version 7, distributed by BYG Systems, Nottingham, UK.
2. Industrial Robotics, Groover, Weiss, Nagel, Odney, McGraw-Hill Publishers, 1986.