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Robotic Control of Tunnelling Machines

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ROBOTIC CONTROL OF TUNNELLING MACHINES

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Abstract. Research is described into the application of robotic techniques to the control of mining machines for tunnelling, heading, ripping etc. Field results are presented showing improved load-control when driving on a single axis. Proposals and simulation results for simultaneous control of both axes are then considered. The interaction of the load/profile control system with the steering of the machine in pitch, yaw and roll modes is also described and an examination of alternative methods for reference profile generation is also included.

Keywords. Robotics, tunnelling, mining machinery, interaction, control, automation, multivariable systems.

INTRODUCTION

Early tunnelling machines were of the full-face type having a single circular cutting-head of diameter equal to that of the tunnel providing little scope for adjustment to tunnel shape. With such machines, it can also be difficult to access the cut debris for loading-out purposes. More recently, machines of the boom-type have evolved, inspired partly by success with smaller machines designed for ripping, road-heading and dinting in coal mines. These employ a rotary cutting-head of much smaller diameter carried at one end of a long boom pivoting at the other end within a rotating turret carried by the mainframe of the machine. The turret may be vertical (as with a military tank) or horizontal and, by appropriate adjustment of boom-angle and turret-rotation, the head may, in principle, be swept along any chosen trajectory within the desired cross-sectional profile of the tunnel. The two types are shown diagramatically in Fig. 1 along with a more novel robot-like double-jointed-arm mechanism (DJAM) driven independently at shoulder and elbow. In contrast to full-face machines, which are advanced continuously into the rockface whilst cutting, the machines of Fig.1 generally cut at a constant depth of sump, with sumping and profile-cutting taking place sequentially. One or more sumps may take place per advance of the machine's mainframe which may be track- or anchor-mounted. Supporting side-anchors may still be required by tracked machines to counteract heavy cutting loads. A tracked horizontal-turret machine (minus anchors) is shown in Fig. 2 cutting a D-shaped profile, simultaneous manipulation of both boom-angle (and hence radius, r) and turret-rotation, α, being clearly necessary to cut the straight sides and flat floor.

The paper outlines the results of studies carried out so far by the authors at the University of Sheffield on NCB and SERC contract into the problems of profile-control and its interaction with other important control problems such as cutting-load regulation and machine steering.

EXPERIMENTS IN LOAD-CONTROL

The seriousness of the load-control problem has been emphasised by frequent damage to the £50,000 reduction gearbox through which the head of a 300kW, 6 m prototype horizontal-turret machine is driven. The speed of boom travel had been manually controlled but with cutter-motor power providing a simple proportional feedback in the event of loads exceeding motor rating. Considerable load fluctuation had been recorded nevertheless.

Restricting attention initially to circular trajectories (i.e. r constant, α manipulable), dynamic analysis and simulation based on Fig. 3 soon reveals the instability of proportional control once the controller gain is raised sufficiently to reduce the inherent error of this Class-O system to an acceptable value (say 10%). Classical lead/lag compensation was effected producing the performance improvements shown graphically in Fig. 4 at a limestone mine in Derbyshire, U.K. Fig. 5 shows the improvements achieved simultaneously in the cutting pattern. The low-frequency servo-oscillations are clearly eliminated as predicted theoretically but high-frequency chatter remains. Fortunately the chatter does not adversely affect the controller operation. The chatter was also predicted theoretically and results from the similarity of the stiffness of cutting k_c, the crowding force p.u. bite and λ_b the stiffness of the boom structure and its hydraulic drive. Only by an increase to the latter can this source of load oscillation be eliminated, (although some schools of thought favour a low structural stiffness to cushion initial impact between head and rock).

PROFILING UNDER LOAD-CONTROL

Fig. 2 indicates the need for simultaneous manipulation of both drives to the boom mechanism when a horizontal-turret machine is called upon to cut curves other than circular arcs centred on the turret axis, or straight lines radiating therefrom. With any type of machine, however, the need for simultaneous drive operation will arise. The vertical-turret machine for instance, whilst ideally suited to cutting horizontally or vertically across the rock face using only one drive at a time, can only produce rectangular tunnels when used in this manner:

a shape that is rarely required. The DJAM was designed with careful choice of arm and head dimensions for the extraction of a near D-shaped excavation with a complicated sequence of independent manoeuvres of Θ (the primary-arm angle) and ϕ (that between arms). The objective could not be totally achieved however and mechanical constraints have since enforced considerable simultaneous drive operation.

Initial attempts to cut a flat floor with the aforementioned horizontal-turret machine were purely mechanical involving a turret-mounted cam actuating the boom-tilting cylinders (via servo-hydraulics) to reduce and later increase the radius of cutting at appropriate points in the turret's rotation. Such movements affect the load-control adversely however, so posing the general problem of how to actuate both drives, of whatever machine, to follow any given trajectory within its reachable envelope, whilst retaining control of the cutting load. (The DJAM poses the additional problem of limiting the secondary drive torque, on occasions of low cutting radius, to avoid self-inflicted damage to the transmission at this point).

After considerable thought and simulation, the scheme finally decided upon is that illustrated in Fig. 6. Suffix d denotes demanded-, or reference-value: Rather than storing tabulated reference trajectories in the form $r_d(\alpha)$ or $\alpha_d(r)$ for horizontal turrets, $y_d(x)$ or $x_d(y)$ for vertical turrets and $\Theta_d(\phi)$ or $\phi_d(\Theta)$ for the DJAM, which is really the cam-principle mentioned above, the reference profiles are formed instead as <u>two</u> tables i.e. $r_d(\ell_d)$ <u>and</u> $\alpha_d(\ell_d)$, $y_d(\ell_d)$ <u>and</u> $x_d(\ell_d)$ and $\Theta_d(\ell_d)$ <u>and</u> $\phi_d(\ell_d)$ respectively, depending on the machine type. Distance ℓ_d is the desired distance to be travelled along the desired trajectory. Simple feedback controls then compare say, r_d and α_d with measurements of r and α from shaft-encoders and the processed errors actuate the servo-valves controlling the appropriate drives.

Distance ℓ_d is merely obtained by integration of demanded velocity signal v_d, which is the output of a load-control algorithm identical to that used earlier on the independent drive trials. The demand v_d, can alternatively be set manually (subject to overriding load limits) or by a secondary torque feedback control law. In any event the speed/load/torque-control problem is thus virtually separated from the profile-control problem. Separation is not total as the simulation results of Fig. 7 show. Some disturbance of the load does occur at the discontinuities of the profile and disturbances in, say, cutting hardness can cause some transient deviation in the cut profile but interaction is negligible to that produced by other schemes. Complete elimination of load/profile interaction remains an area for future research but it is hoped to present, at the Symposium, practical results of the scheme outlined from surface cutting trials scheduled for early 1986.

INTERACTION BETWEEN STEERING AND PROFILE CONTROL

With full-face tunnelling machines, steering is usually effected by hydraulic adjustment of the angle of attack of the machine body with respect to the anchors braced against the circular tunnel walls. Such steering action is, of course, cumulative since these are the walls previously cut by the machine itself and, to prevent looping the loop, steering adjustments must be applied only in a transient manner. Boom-type machines must be steered by shifting the whole reference profile up-and-down or side-to-side or by distorting part of the profile in the appropriate direction. Because of the discrete sumping method of machine advancement (mentioned above), such deflections cause definite steps in the tunnel overwhich the machine tracks must subsequently ride and against which anchors must be braced. The step-size must clearly be limited to avoid toppling and to avoid stress concentration on tunnel supports. Fig. 8 shows the results of preliminary simulations of the vertical-steering of a horizontal-turret single-boom machine having a boom length = base-length = 6 sumping distances. Steering is here accomplished by adjustment of the leg-length of the D-shaped outer profile rather than by whole-profile deflection. Control is based on proportional height feedback of deviations from a laser beam aimed down the tunnel together with tilt feedback from a pendulum or spirit-level inclinometer.

Although reasonably encouraging, these results raise important questions covering how the machine traverses a variably stepped floor and how profiling errors, evident in Fig. 8 , might create pitch, yaw and roll problems. These errors have now been much reduced by introduction of the profiling scheme of Fig. 6 and alternate clockwise and anticlockwise cutting should combat roll effects highlighted in Fig. 9. Long term simulation runs with more detailed models are necessary however to check out cumulative effects.

As regards the traverse of stepped floors and the attitude of side-anchors braced on stepped walls, considerable investigation has taken place and continues. Whereas Fig. 8 is based essentially on assuming contact points only at front and rear of the machine base-frame, i.e. a simple 4-wheel model, subsequent research has produced a simulation that fits a flat base to any stepped floor, the length of the base, boom, and cutting-head together with the sumping-distance, centre-of-gravity and height-sensor locations all being freely adjustable. The model employs linear programming to determine that position and attitude of the machine for minimum potential-energy. A typical result is shown in Fig. 10, somewhat compressed horizontally. Although this particular machine geometry is clearly stable (after initial transients), some arrangements are revealed to be unsteerable. The program has yet to be adapted for roll studies involving steps which vary across the tunnel floor (Fig. 9). The modelling and computational burden, already large for pitch studies, may well prove to be impractical in the short term.

REFERENCE TRAJECTORY GENERATION

Various methods have been investigated for generation of the reference trajectory of the cutting head across the rock face. For preliminary simulation of the various profile control algorithms (of which the scheme of Fig. 6 proved to be best) piecewise analytical curves such as the D-shape of Fig. 7 were sufficient. Parametric equations for, say, r_d versus ℓ_d and α_d versus ℓ_d (for the horizontal-turret machine) were readily derived and, from these, look-up tables were calculated and stored. The approach is inflexible, however, as new equations must first be derived for any new trajectory that might be required.

To overcome the problem of inflexibility, classic robot "teach and learn" methods were also tried whereby an operator would attempt to drive the simulation along some chosen curve using his two manual controls simultaneously. A V.D.U. displayed the curve produced. Whereas the method is ideal for continuous lightweight manufacturing robots e.g. for paint-spraying, where the machine can be literally led by the hand or for discrete-point trajectories as required in, say, spot-welding, it proves to be unsuitable in this heavy mining application. Even after much practice, the driver is able to produce only the coarsest approximation to the desired curve due to mental coordinate conversion difficulties and the interposed machine dynamics.

The method adopted has been to take the desired curve drawn on graph paper, break this up into straight-line or circular segments (not necessarily concentric with the machine's axes), and to enter the break points into the computer as pairs of cartesian coordinates. A mid-point is also needed for the circular arc segments. Analytic formulae can then generate the segments continuously at a speed set manually or indeed by the load-control system at run time so obviating the need for large look-up tables. Any drift due to discretisation is corrected back to the known break-point at the end of each segment. The principle of Fig. 6 is retained but the velocity demand v_d now generates the machine servo references by formula rather than by table.

The references are regenerated firstly in cartesian form, any shifts or tilts forsteering purposes are superimposed, and coordinate-conversion routines then used to produce r_d and α_d and/or Θ_d and ϕ_d from y_d and x_d depending on the machine type. Conversion to Θ_d ϕ_d can produce two solutions in general depending on whether right- or left-handing of the elbow is chosen, and, in some situation, only one of these is allowable because of the constraint $90^o<\Theta<270^o$. A time-optimal control problem is thus posed or when best to change hand to minimise the total cutting-plus changeover-time. This is a subject for further research.

CONCLUSIONS

Field trials have confirmed predictions from analysis and simulation that the load-control of tunnelling machines can be stabilised by classical compensation methods when only a single axis is driven. For combined load- and profile-control using both machine drives, a parametric representation of the desired trajectory is needed, distance ℓ_d measured along the curve being the independent parameter. The distance ℓ_d may then be derived from an identical load-controller to that for single-axis operation and stability retained. Whilst being much reduced, some load/profile interaction remains and is worth further investigation.

Preliminary methods for and results of simulation of pitch- and yaw-steering have been presented, based on linear-programming to find the minimum potential energy position of the machine on the steps produced by the cutting-head. Though these are encouraging, further work is needed particularly to investigate roll-effects.

Studies of reference-profile generation methods have favoured the computer-reconstruction of trajectories broken down into straight-line and circular segments via analytical formulae in preference to data-tables produced entirely analytically or by classic robot-teaching methods. DJAM's ideally demand the solution of a time-optimal control problem where reference trajectories impinge mechanical constraints on elbow or shoulder movement.

LIST OF SYMBOLS (For Figures 1 to 7)

DJAM = double jointed arm mechanism
d = suffix denoting demanded value
f = viscous coefficient
F_{ab} = force applied by boom
F_{cb} = crowding force
k_c = rock-hardness coefficient for crowding force
k_h = rock-hardness coefficient for cutting power
k_m = 1/(cutter-motor efficiency)
k_ℓ = load controller gain
k_{pr} = radius loop gain
k_{pa} = rotation loop gain
ℓ_d = demanded distance along reference trajectory
M_b = effective mass of cutting head+boom
P_i = cutter motor power consumption
P_m = cutter motor power output
P_r = reference power signal
r = radius of cut about machine axis
s = Laplace variable
T = delay between lines of cutting picks
T_h = hydraulic servo lag
T_m = cutter motor lag
u_α, u_r = demands on hydraulic servos
v, v_d = velocity of cutting head, & demanded value
λ_b = boom & drive stiffness
α = turret rotation angle
Θ = angle of DJAM primary arm
ϕ = angle between primary and secondary arms
τ_1, τ_2 = torques on primary and secondary arms

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Fig. 1. Types of Tunnelling Machine

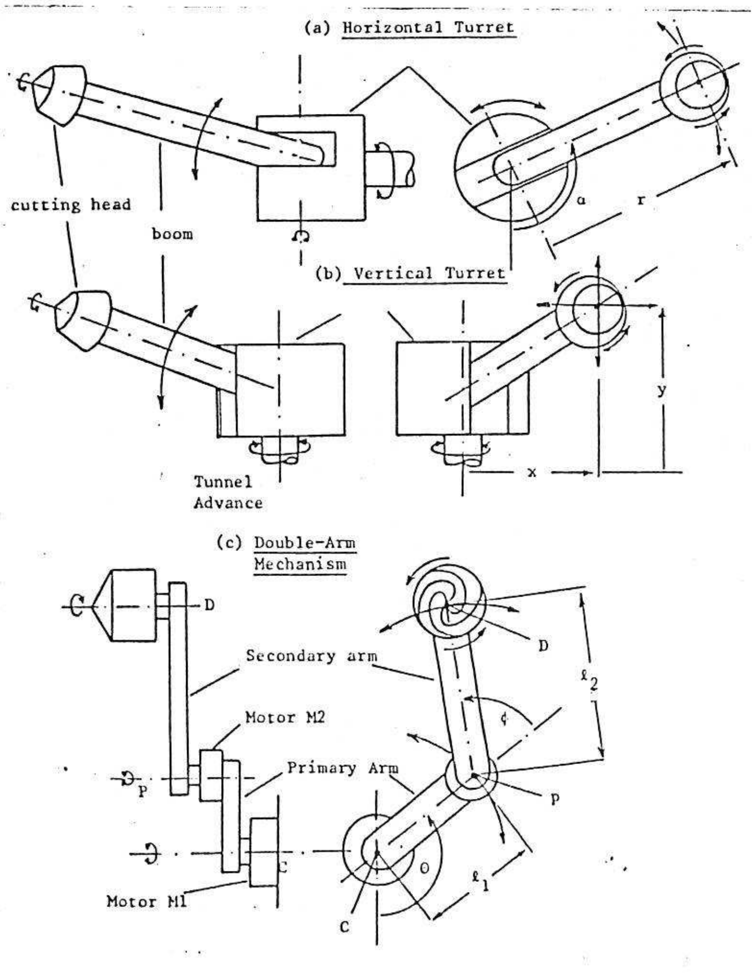


Fig.2 A Track-Mounted Machine with Horizontal Turret

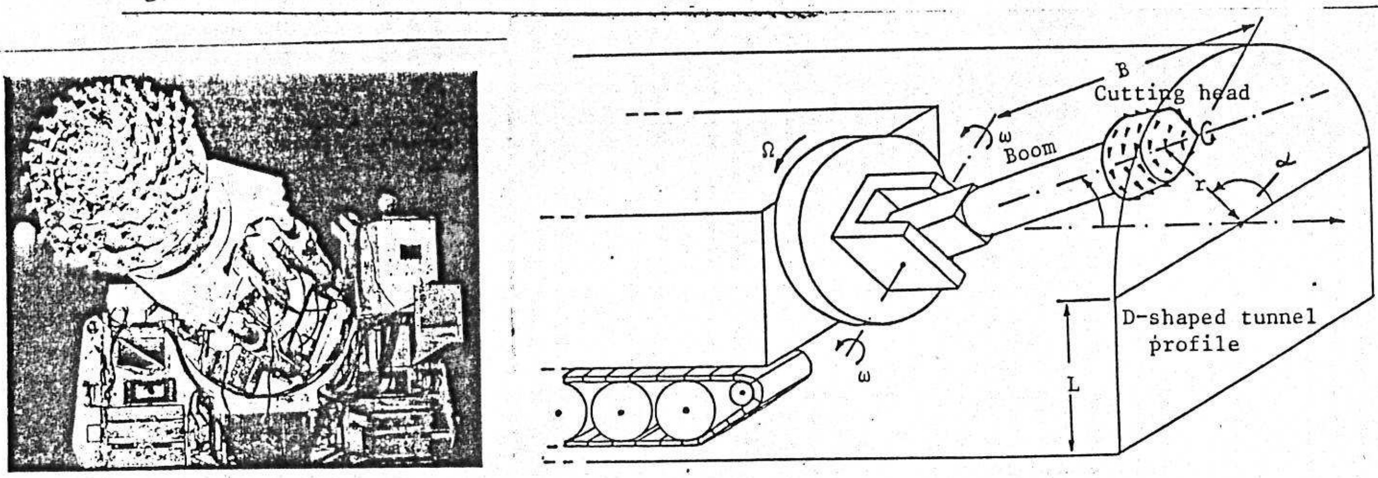


Fig.3 Dynamic Simulation Model for Fixed Radius Operation

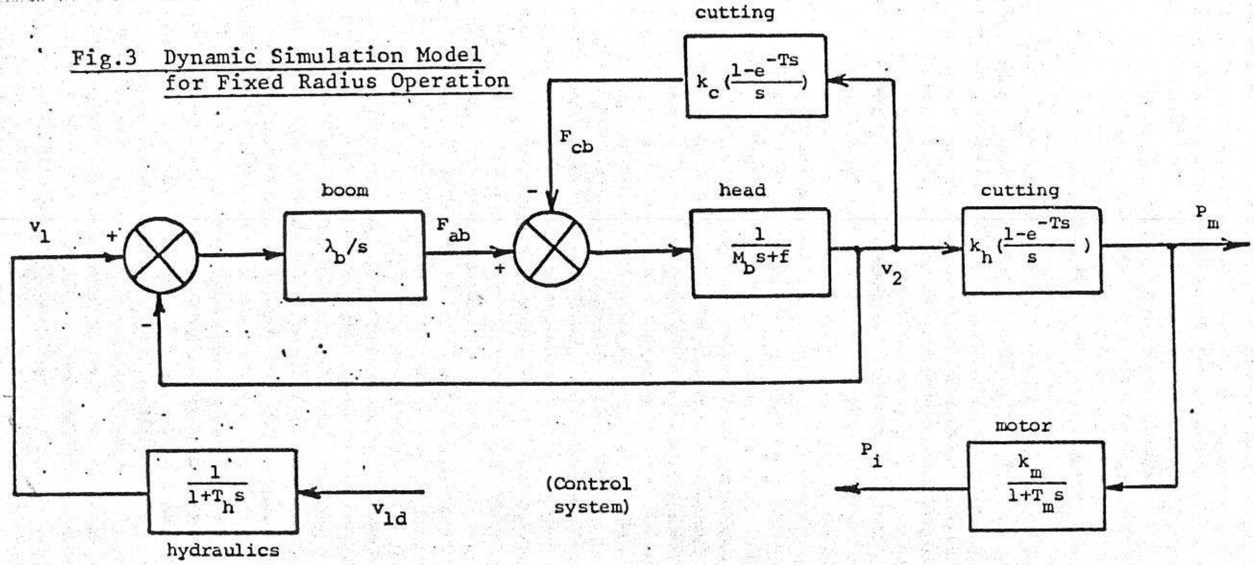


Fig.4 Cutter-Motor Power (a) Before and (b) After Load-Control Compensation.

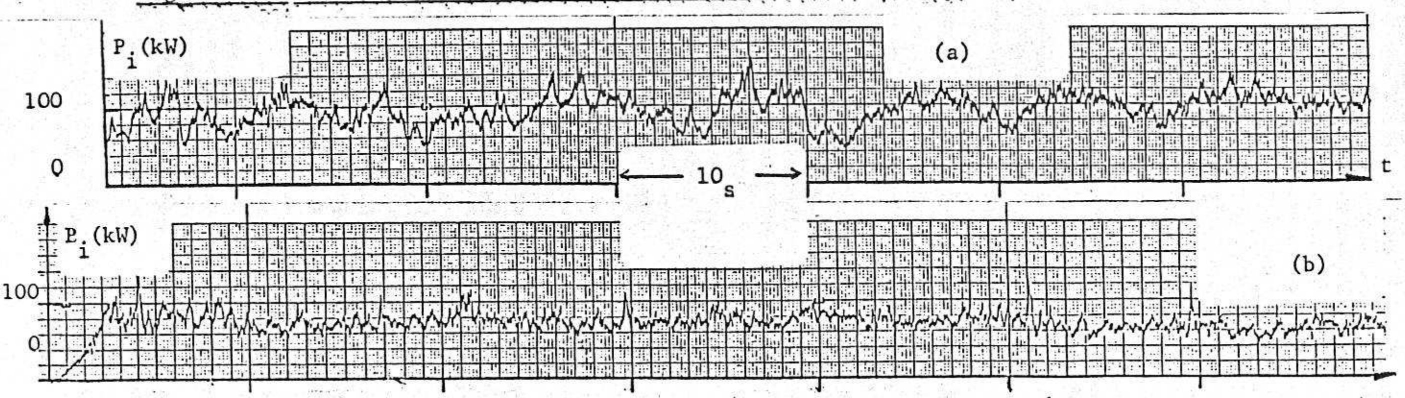


Fig. 5 Cutting Patterns Produced (a) Before and (b) After Compensation.

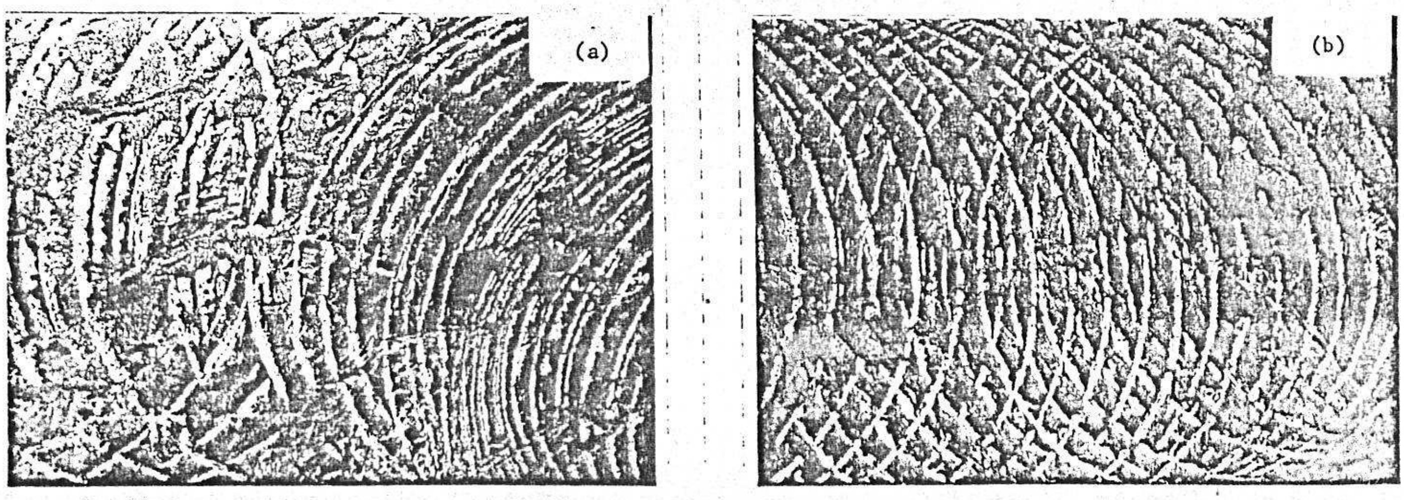


Fig 6. Decoupling Scheme for Load-and Profile-Control

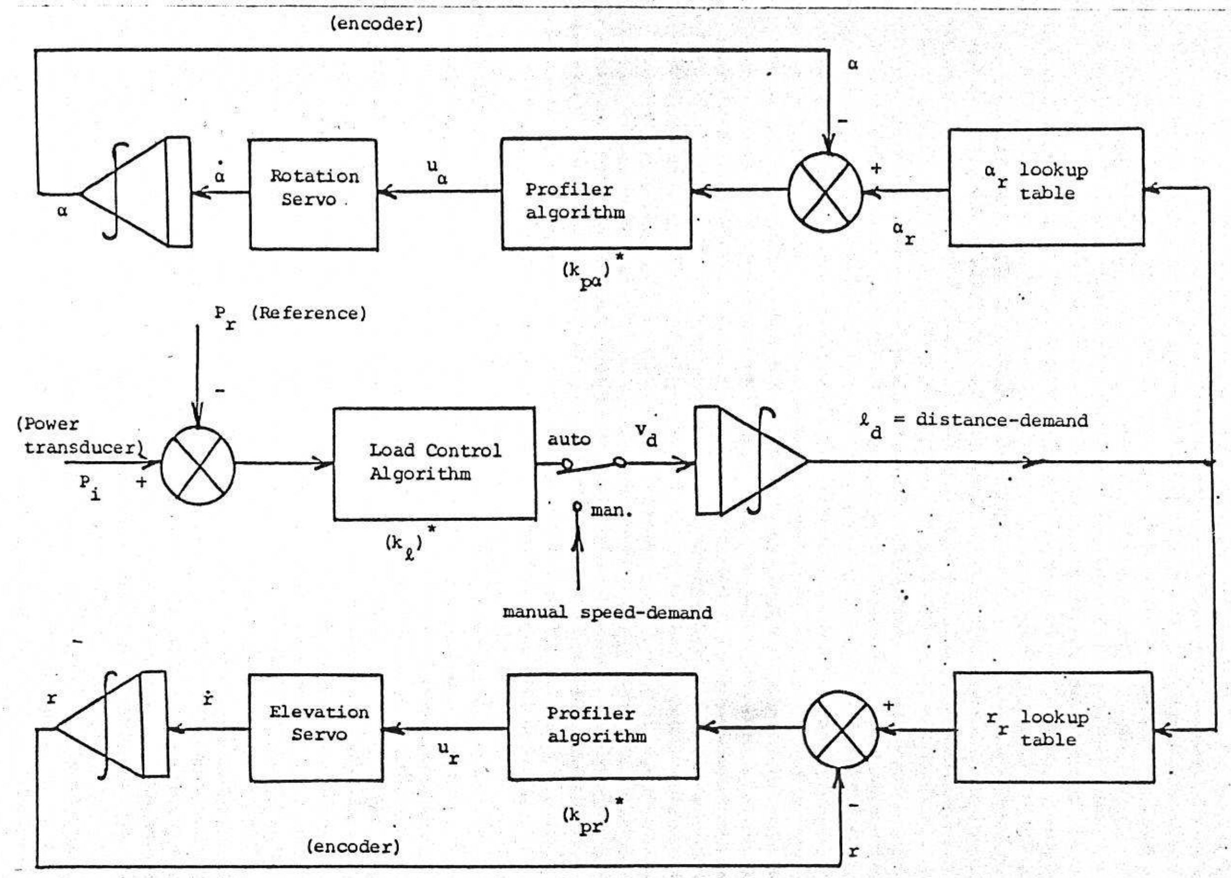
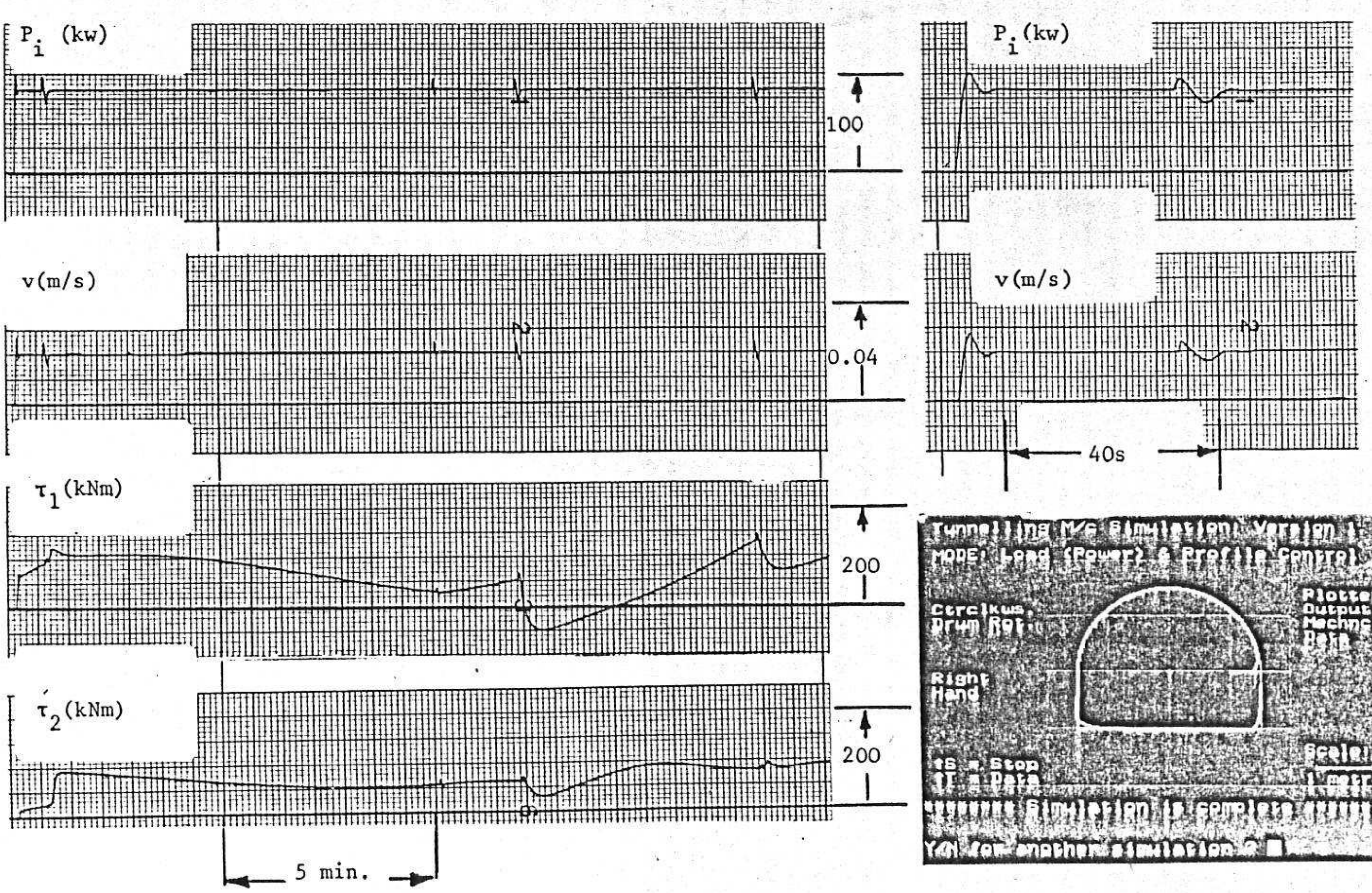
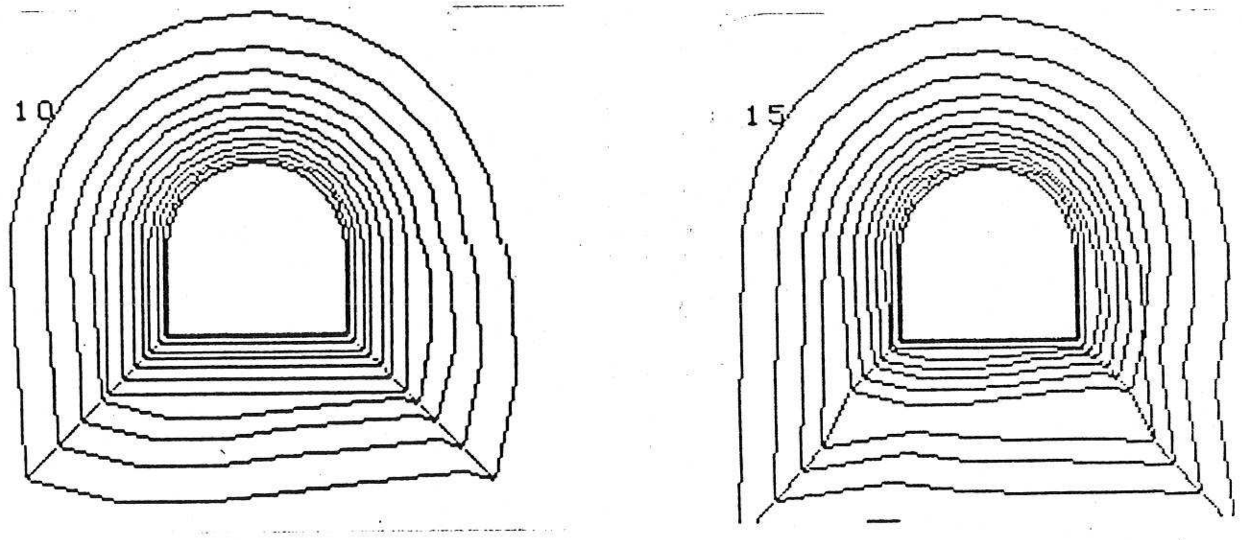


Fig. 7 Simulation Results Using Control Systems of Fig. 6



Profile

Fig. 8. Results from Vertical Steering Simulation using Four-heel Model



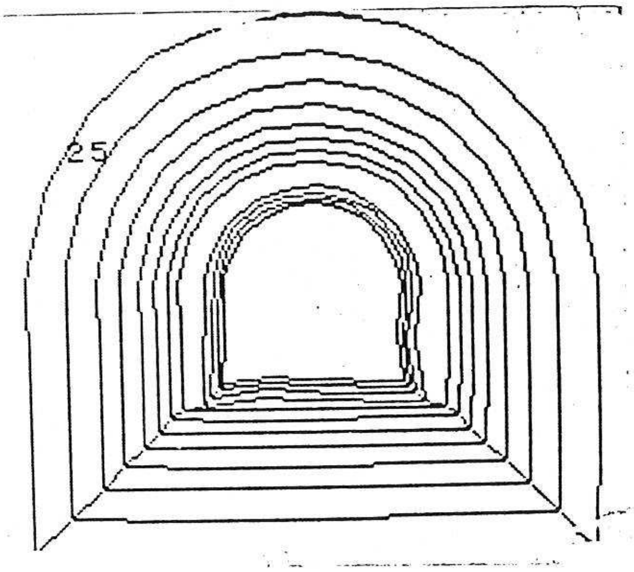


Fig. 9. Interaction between Load, Profile and Roll.

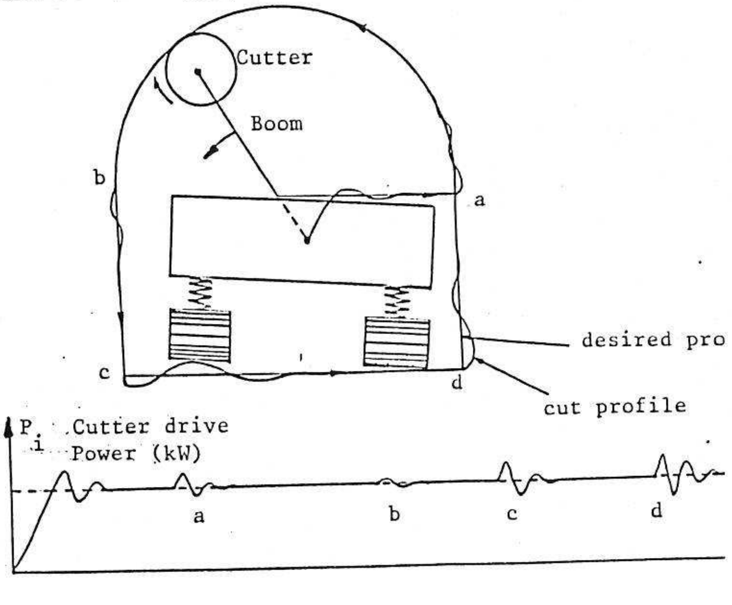


Fig. 10. Results from Vertical Steering Simulation using Linear Programming Model