Align3D: a package for planning rail alignments
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Abstract

Align3D is a computer-based planning package designed to optimise the horizontal and vertical alignment of a railway while complying with various constraints. It uses stochastic optimisation and ‘fuzzy logic’ to generate a selection of low-cost alternative alignments. This enables planners to exercise their professional judgment in balancing the non-quantifiable aspects of the alternatives against their costs. The package is flexible, capable of operating with minimal data at the beginning of a study, yet able to incorporate numerous details and sophisticated constraints as the focus of the study narrows.

1 Introduction

Constructing a new railway or realigning an old one can be an expensive exercise, in which costs depend on the alignment selected. Costs are increased by long lengths of viaduct and tunnel, and by large volumes of cut and fill. They are also influenced by the location of existing railways, roads, services and buildings, and by the financial, social and political impacts of land resumption. The problem is exacerbated for high-speed rail systems or resource development lines where higher geometric standards make it more difficult to follow the terrain and comply with constraints.

The task of designing route alignments that satisfy various geometric and other constraints is a major branch of CAD and is performed interactively with any of a large number of packages running on a wide range of computer platforms. This process can require days or weeks of skilled manpower to locate the route sufficiently accurately for detailed design to begin. As a consequence, the problem of optimising alignments automatically has been the subject of numerous efforts since the advent of CAD.
O’Brien & Bennett suggested a model of dynamic programming based on a rectangular grid to solve the problem of minimising costs. Nicholson et al. suggested a two-stage model, in which the first (approximate) stage was based on O’Brien & Bennett, and the second on an unspecified calculus of variations. Parker suggested an alternative grid-based model for minimising construction costs subject to slope constraints. Trietsch developed a family of methods by which a solution may be sought which was based on four alternative grid searches and four different cost approximation methods.

All of the methods involved some form of grid search, and with a method for calculating the costs for arcs between the straight sections of the route. However, the use of grid search methods meant that the number of points (and the size of the problem) grew very rapidly as the demand for accuracy in the location of the route increased. Some more recent authors (Goh & Chew, and Chew et al.) have attempted to place more emphasis on the calculus of variations that involves the construction of large systems of equations. However, these increase in complexity very rapidly when more detail is required or new constraints are introduced.

None of the attempts to date have been sufficiently successful to be included in commercial packages as a standard tool, and interest has gradually waned. Align3D is based on a radically different approach, and this paper does not attempt to review previous efforts in more detail as they have little in common with Align3D beyond the problem they seek to solve.

2 Planning routes

The border between planning and design is somewhat fuzzy, but discussions can be clarified by attempting to make a distinction. In the context of this paper, planning is concerned with where the route should go, and design is concerned with the definition of the route and the details of the earthworks and other construction. Planning requires much of the information needed for design but in a less detailed form. Design determines the final cost, but planning exercises the greatest influence over costs.

The current approach to planning is to nominate a feasible alignment in plan view by using a contour map as a base and drawing on experience of where the route ought to go in the circumstances. The land profile along this route is then examined and a vertical alignment is nominated with the aim of minimising construction costs. These vertical and horizontal alignments serve as a starting solution for lengthy interactive sessions with a CAD package in which the locations of intersection points are adjusted and the costs of the route recalculated, until a satisfactory compromise is obtained between the criteria that characterise a good design and the cost of construction.

Depending on the length of the alignment, the complexity of the terrain and other constraints, this process can take days or weeks. The time factor tends to discourage exploration of alternatives that differ significantly from the original alignment, so that the cost of the final solution depends critically on the
original choice. As a consequence, while the interactive approach to planning is very good for balancing qualitative criteria against cost, it carries a significant risk of producing alignments that are only locally optimal.

3 Design philosophy

The goal of Align3D is to optimise the location of a route, while satisfying all constraints, not to produce a final design. Because many aspects of a plan are qualitative, the acceptance of a particular alignment as ‘good’ depends very much upon the weight that a planner places on various criteria. These qualitative judgments depend on the organisation philosophy and policy, and should be made by humans. Align3D assists this process by producing a range of low-cost alignments that meet the objective criteria, which the planner can select from or modify on the basis of cost and the qualitative criteria.

Because planning and design are essentially cyclical processes, Align3D was designed to be as flexible as possible in the demands it placed upon data and its ability to satisfy numerous diverse constraints. One of the underlying criteria was that it should be capable of operating with minimum data at the start of the planning process, but be able to incorporate detailed information and sophisticated constraints when necessary.

4 Abilities and data requirements

The abilities of a program and its data requirements are inextricably linked. The greater the detail required from the program the more detailed must be the input. There are no explicit limits to the level of detail that Align3D can handle; the only constraints are the amount of RAM in the computer and the increased computation time.

The factors that need to be considered are:

Terrain
It is axiomatic that the shape of the land will be important. Rugged mountains will require major earthworks not needed on flat plains. The digital terrain model (DTM) employed by Align3D is based on a square mesh; this uses more memory (which is cheap) than an irregular triangulated mesh but produces much faster solutions.

Geotechnical information
As the alignment moves below the surface it cuts through different geological strata. These strata have different physical properties requiring different slopes on the sides of the cut and shoulders between strata. Removing material from different strata entails different costs. Similarly, fill has its own requirements of batter and associated costs. Not all the material removed from cuttings can be used for fill, and the material that is used may compact to a different density. Further, the geological characteristics of a corridor are not necessarily uniform;
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rocky ridges can be separated by alluvial valleys. Align3D can deal with an unlimited number of zones, each with defined geological characteristics.

Linear features
Any route is likely to encounter linear features such as roads, rivers and pipelines. Some features may be crossed ‘at grade’, while others must be crossed ‘grade separated’ and may involve a structure. Further, the angle at which the alignment crosses a linear feature is important. Thus the description required of any feature includes horizontal and vertical clearances and a string of points defining the centre-line of the feature. Align3D accommodates an unlimited number of such features.

Special treatment zones
In addition to linear features, there are often zones that require special treatment for social or environmental reasons. An alignment may need to avoid a particular area, but even when the alignment can pass through a zone it may be forced into a cutting or tunnel to reduce noise or visual impacts, or onto a viaduct with a minimum elevation when crossing a flood plain. Align3D caters for special treatment zones in which various crossing constraints can be enforced, or from which the alignment can be prohibited completely.

Geometric standards
Align3D allows different minimum radius curves in plan and profile, and lets the maximum gradient depend upon direction of travel. (This can be important on lines where trains haul freight in one direction only, and return empty.)

5 Costing the alignment

The nature of construction depends on the altitude of the alignment relative to the natural surface, and any structures required by crossings. To estimate these costs the alignment is divided into short segments on which the nature of construction remains constant and can be quantified relatively easily.

Structures
The cost of tunnels is proportional to their length, while the cost of viaducts is a linear combination of their length and their profile area. That is, the cost of a unit length of viaduct includes a fixed component for foundations plus a variable component that is proportional to the height of the viaduct.

Cut and fill
The volume of cut and fill is obtained by averaging the cross-sectional area at the start and end of the segment and multiplying by its length. The calculations consider the magnitude of the cross-slope of the natural surface. If the spread of the earthworks would be excessive, Align3D incorporates a retaining wall on the appropriate side of the earthworks. The retaining wall reduces the volume of material to be moved but adds to the cost of construction of the wall.
Transportation of material
The volume of material and the distance that it has to be transported also contributes to the estimate of cost.

6 Optimisation technique

Optimising an alignment is complicated by the existence of many local sub-optima. For instance, passing through a special treatment zone can be very expensive, while passing to the left or right is substantially cheaper. The complexity of the land surface itself contributes in a similar fashion; running up a different valley or along the opposite side of the valley can produce alignments that are locally optimum, but considerably more expensive than the best available. To be effective, the optimisation technique must be capable of escaping from a high-cost local optimum to a better one even if this involves temporary alignments with still higher cost.

The technique employed by Align3D is a form of stochastic optimisation. A randomly selected intersection point is moved at random subject to the geometric constraints described earlier. The cost of the modified alignment is calculated and compared with the cost of the old one, and a decision is made to accept or reject the change. Once a decision has been made, another intersection point is selected at random and the process repeated.

The ability to escape from local sub-optima is provided by the incorporation of a value, referred to as the rejection threshold, into the decision process. A move is accepted if the new cost is less than the old cost plus the rejection threshold. Initially the rejection threshold is very high but as the optimisation proceeds the rejection threshold is slowly reduced to zero and only those moves that lead to a reduction in cost are accepted.

The algorithm does not guarantee that the alignment will escape from local sub-optima; it merely makes it possible. However, careful selection of the initial rejection threshold and regulation of the rate at which it is reduced can greatly increase the probability of reaching the global optimum. If the initial value is too low or reduced too fast, the alignment is more likely to be trapped in a sub-optimum. On the other hand, if the initial value is too high or reduced too slowly, the time required may be excessive.

Continuing the optimisation process beyond a given accuracy may solve a theoretical problem but it does not contribute significantly to the solution of the practical problem. Accordingly, the optimisation stops when the spatial range of the acceptable moves made by the intersection points declines below a set value that depends on the accuracy of the digital terrain model.

7 The output

The alignments produced by Align3D are in essence splines, in which gradient, curvature and rate of change of curvature are controlled by the geometric
standards specified for the route. They are represented as strings of (three-dimensional) points located at fixed intervals along the centre-line.

The complexity of the land surface and constraints, and the stochastic natures of the procedure, mean that Align3D does not yield the same answer each time. Rather, 50 runs are likely to produce 50 different alignments; each a local optimum in which displacing any one of the intersection points will increase costs.

The multiple solutions tend to be clustered in families that depend on their behaviour with respect to the more significant features of the corridor. Because of the stopping criterion, all alignments are only approximately locally optimal, in that moving a single intersection point more than a short distance cannot reduce costs. This multiplicity of solutions is an outcome of the optimisation procedure employed and it has the very positive effect of answering some of the ‘what if’ questions that arise as part of the normal planning process (what if we tried this variation? or that variation?). If a variation is at all comparable in cost with the best solutions it will probably appear in the list of possible solutions. If a variation is relatively expensive will be unlikely to appear. This allows the planner to make judgments about the relative desirability of various ‘low costs’ solutions and balance these against the objective estimates of their costs.

8 Case study

Align3D has been tested on nine data sets to date. In all the cases Align3D produced an alignment that was at least as good as that produced by the design engineers, but in a far shorter time. The extent to which Align3D bettered upon the alignments produced by the designers was sometimes difficult to quantify as the cost estimates for the original alignments were usually not available to the author.

One data set involved an alignment for a very-high-speed railway through mountainous terrain. The optimisations were performed in cooperation with the consultants working on the project as part of the development and testing of Align3D. The corridor was approximately 90 km long and averaged 8 km wide. The alignment climbed over 800 m from start to finish, and the terrain ranged from sea level to 1100 m. The alignment was complicated by the presence of 15 exclusion zones representing National Parks, Nature Reserves and such like.

Because the line was intended for operation at approximately 350 km/h, the geometric standards specified for the alignment were very high with extremely large minimum radii of curvature in both plan and profile. The standards were:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of finished surface</td>
<td>15 m</td>
</tr>
<tr>
<td>Drains on cut side(s) of finished surface</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Maximum gradient</td>
<td>3.5%</td>
</tr>
<tr>
<td>Angle on fill slopes</td>
<td>27°</td>
</tr>
</tbody>
</table>
Angle on cut slopes (stratum 1) 34°
Angle on cut slopes (stratum 2) 45°
Depth to base of stratum 1 10 m
Minimum horizontal radius of curvature on centre-line 7000 m
Minimum vertical radius of curvature 22 000 m
Cost of viaduct $20 000/m
Cost of filling $3.50/m³
Cost of cutting $6.50/m³
Cost of tunnel per metre $20 000/m

The costs from a set of 45 optimisation runs ranged from $371 000 000 upward, with 15 of the runs being under $450 000 000 and 30 under $500 000 000.

The cost obtained by the consultants for their alignment was in excess of $600 000 000, but direct comparison is difficult because the data provided did not include the location of rivers and roads and their associated crossing constraints. To accommodate this it would be necessary to add an arbitrary length of viaduct (say 3 km at $20 000 000/m). A further complication was that the original constraints were incomplete and that the alignment had to be out of sight of some of the exclusion zones, not just avoid them. This necessitated tunnelling, and a quick experiment with an additional special treatment zone that required tunnelling in the critical area, yielded costs that were still some 20% lower than those produced by the consultants.

Spot checks by the consultants along the route confirmed the volume calculations. Further, Align3D achieved its results while meeting all the geometric standards, while the consultants were forced to reduce minimum horizontal radii to 4500 m and increase the maximum gradient to 5%.

9 Discussion

Align3D is fast and flexible, and able to generate low-cost solutions in a very short time. Once the initial database is established the package can be used to explore different scenarios, and obtain realistic costs for various environmental protection measures or changes in design standards.

Because it can explore the corridor thoroughly, Align3D produces alignments that match or better those produced by other techniques. The savings in costs are hard to quantify because they depend to a large extent on the environment of the route. If the problem were to optimise an alignment across an uninhabited level plane, Align3D could not produce an improvement over conventional techniques. However, most problems are not so simple, and Align3D can provide the greatest assistance in the most complicated cases. It is immaterial whether the complications arise from the complexity of the terrain or the nature and number of additional constraints and costs imposed on the route.
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10 References


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