AN EVOLUTIONARY APPROACH TO GENERATING CONSTRAINT-BASED SPACE LAYOUT TOPOLOGIES

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Abstract

This paper describes a system to produce space layout topologies for architectural plans using an evolutionary approach. The layout specification is defined as a set of topological and directional constraints, which are used as a fitness function in the evolutionary system. The halfplane representation is used to represent the genotypes in the evolutionary system, for both arrangements of halfplanes and the figures generated from those arrangements. As the halfplane representation proposed here does not distinguish between straight and non-straight boundaries, at the symbolic level the spaces and the layouts produced can also be bounded by straight or non-straight lines. The well known rectangular (polyomino) arrangements become a particular case only.

1. Introduction

Space layout planning problems have been addressed by many researchers (Buffa et al, 1964; Liggett, 1980; 1985; Steadman, 1983; Akin et al, 1992; Yoon and Coyne, 1992; Jo and Gero, 1997) among others. They have presented many different approaches, synthesizing layouts using generative grammars, constructive placements, genetic algorithms, etc., addressing topological, directional and geometrical issues. The most common representation is placement (or generation) of rectangular units on a plan in dimensionless form (Steadman 1983). In this type of representation a coarse granularity layout of a house is similar to that shown in Figure 1(a). Many interpretations can be derived from this type of representation, such as topological relations and symmetries. The other major research direction is concerned with determining, from the constraints on area, width and length of each space, the optimal dimensions according to some criteria. It is quite common to map the layout shown in Figure 1(a) into the graph shown in Figure 1(b). The graph represents the topological relationships between rooms, where the nodes represent the rooms and arcs represent the adjacency between them (Miller, 1971). Many interpretations can be based on these graphs, such as conditions for planarity, coloured and weighted graphs, etc.

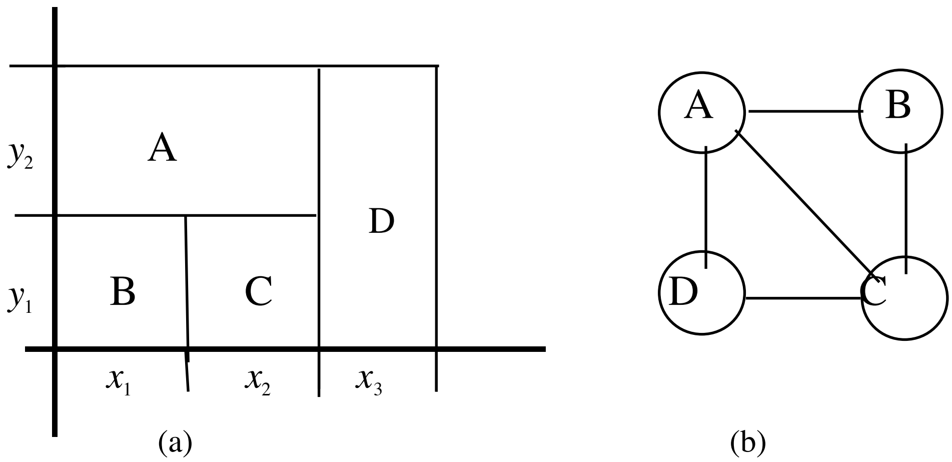


Figure 1: (a) A coarse granularity layout of a house in a dimensionless space, and (b) its equivalent graph of adjacency between rooms.

The dimensioning of floor plans have been tackled using various optimization techniques, including linear programming (Mitchell et al, 1976), and nonlinear and dynamic programming (Gero, 1977). Jo (1993) attempted to solve the topological and geometrical problems together by using a evolutionary approach, where a set of shape rules generates a space plan and the geometrical constraints are evaluated with a fitness function based on multiple criteria.

2. Background

The planning of space layouts has two levels of solutions: topological and geometrical. At the topological level there is interest in the relation among the spaces as invariant properties of the layout under any geometrical transformation. At the geometrical level the focus is on numerical values of each space, such as area, length, distance, etc. In this paper we proposed a system to tackle the first level: finding arrangements of lines that generate a set of spaces valid under the desired topological constraints. As an example of such constraints we may have the following statement of requirements which can be treated as a set of topological constraints:

A house has 7 spaces: room1, room2, room3, living, kitchen, bathroom and a corridor. The space room1 must be adjacent to room2 and to the corridor. The space room3 must be adjacent to the bathroom and to the corridor. The living must be adjacent to the corridor but not adjacent to room1, room2 or room3. The kitchen should be adjacent to the corridor. The space room3 should be on the left of room1.

This set of constraints has the potential to produce a large set of possible solutions and is computationally complex to solve. To deal with such complexity we develop an evolutionary system that starts with some basic layouts and evolves them based on their suitability (fitness) compared to the topological constraints.

The basic representation for use in the genotype of the evolutionary system is the *halfplane*. In this paper it will be used to construct spaces.

3. The Representation

The basic representation used in the genotype of the evolutionary system is a halfplane. The halfplane representation has been used successfully in other applications (Damski 1996, Damski & Gero 1996, Gero et al. 1995) as the basis of a formal system of representing shapes founded on logic. Such a formal representation has been used to reason about spaces. Here it is used to construct spaces.

In the halfplane representation there is no line dividing a plane, but an abstract border. This abstract border divides the plane into two non-overlapping areas, as shown in Figure 2. The division of a plane into only two halfplanes has the advantage of reducing the complexity of the logical representation to two-value logic, such as propositional and predicate logic. In this way we can arbitrarily assign the truth value **true** to one side and **false** to other.

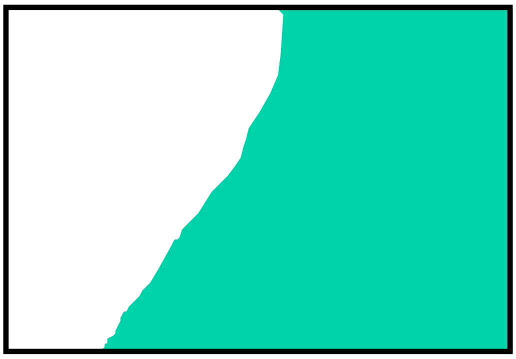
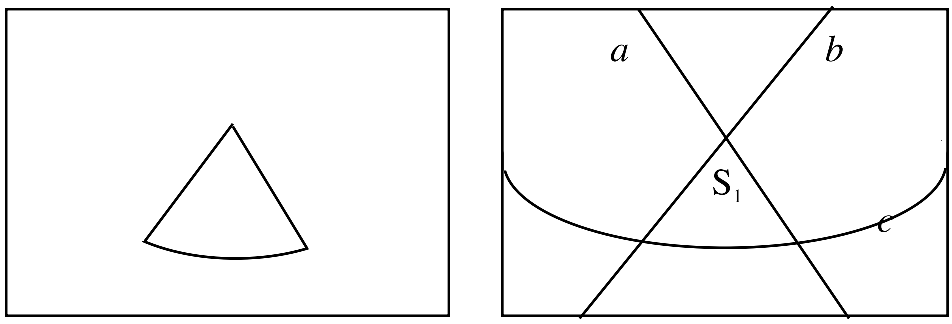


Figure 2: Two halfplanes – one shaded and the other unshaded.

In order to represent a shape using the halfplane representation it is necessary to map each geometrical line in a figure into a halfplane, and then map the halfplanes into logic. Figure 3(a) shows a figure with 3 lines, which is re-represented as halfplanes in Figure 3(b). The shape $\mathbf{S_1}$ has the logical expression hp(a) □ hp(b) □ □hp(c), which means the shape is on the **true** value side of halfplane *a* and *b* and on the **false** side of halfplane *c*. The logical expression that defines this arrangement is given by the formula □hp(a) □ □hp(b) □ □hp(c), because it is always true that the region defined by □hp(a) □ □hp(b) is inside the halfplane □hp(c). With this information it is possible to determine all possible regions with the halfplanes and the topological information among these regions. It is interesting to note that the representation is the same regardless of whether the boundary is a straight line or not. With the halfplane representation it is possible to reason about the shapes at both the topological and directional levels (Damski, 1996).



(a) (b)

Figure 3: (a) Primary shape, and (b) the halfplanes *a*, *b* and *c* derived from the primary shape.

We can label one halfplane as "0" and the other as "1" (the geometrical line which may be thought to exist at the border can reside in either sides without changing the representation). For any given two halfplanes, it is possible to divide a plane into four or fewer distinctive parts, labelled: "00", "01", "10" and "11". Each one of these parts, defined as a region, represents the smallest space in an arrangement of halfplanes. For a given arrangement of *n* halfplanes, each region is represented as an ordered bit-string [00101…1] with *n* bits.

Shapes are formed by the composition of regions. Shapes have topological relations among them. In architectural examples each shape represents a space within a layout. The evaluation of the topological relations among the shapes against the constraints initially specified composes the fitness function value of a given arrangement of halfplanes.

Using the genetic algorithms approach (Goldberg, 1988) it is possible to represent a set of halfplanes in a genotype as a bit string. From this arrangement it is possible to generate a population of shapes. Each set of shapes can be evaluated against the topological and directional constraints. The shapes and their configurations are evolved until a desired level of fitness is reached. The best result is passed on to the initial arrangement of halfplanes. In this cycle it is possible to evolve halfplane arrangements at a non-numerical level and derive space layouts that fulfill the initial requirements (used in the fitness function). All these operations are performed using the logic representation.

4. The Evolutionary System

The evolutionary system operates at two hierarchical levels: arrangements of halfplanes and arrangements of figures. Each arrangement of a set of halfplanes produces a set of regions. A population of arrangements of halfplanes, initially randomly generated, is evolved according to the results given from the possible set of shapes generated from the regions resulting from each arrangement. The standard roulette wheel system of evolutionary systems (Goldberg 1988) selects some arrangements of halfplanes to be "parents" of the next generation using both crossover and mutation mechanisms.

For each particular arrangement of halfplanes a number of possible figures are generated. This population of figures is evaluated against the desirable constraints. The Pareto optimization technique is used as a selection criteria for the next generation of figures. Pareto optimization was chosen to handle the disparate criteria defined in the topological constraints. The fitness value of the best figure in a given population is passed upwards to the related arrangement of halfplanes.

The description of this system is:

- a set H of halfplanes is generated
- a population of arrangements of halfplanes is generated, where every member H_i is a subset of H
- for each H_i, generate a set of layouts (set of figures) L
- each layout in L is evaluated against the set of constraints
- the layouts are evolved according to the results of the fitness function
- each arrangement in H_i is evolved according to the evaluation of the population of layouts in that topology.
- arrangements are evolved in H.

This is a hierarchical evolutionary system. The first level evolves arrangements of halfplanes and the second level evolves layouts. At the second level it is necessary to use a multicriteria system in the fitness function, such as the Pareto optimization schema.

5. Implementation and results

The evolutionary system was implemented using part of the system developed in Damski (1996). The evolutionary component was implemented in Prolog. The system initially generates a population of halfplanes at random. For simplicity we generated halfplanes with straight boundaries. In addition, because of the building layout application, all the boundaries of the halfplanes are set parallel or orthogonal to each other. Examples of those arrangements are shown in the Figure 4.

From the population of halfplanes, a population of arrangements of halfplanes is generated. For each arrangement we generate a population of figures and evolve them.

This evolution is based on a set of criteria. In the example shown in this article we used only 3 criteria:

- Shape connection: this criterion checks if all parts of a shape are contiguous, because the selection at random can create non-contiguous shapes. In order to improve the algorithm we generate and evolve them contiguously.
- Shape overlapping: this criterion looks after shapes that overlap another shape. In the layout case shapes should not overlap each other.
- Shape adjacency: while the first two criteria were basic for any layout, this one sets how we want to relate, topologically, all shapes in the same layout. In our example we define a layout with three shapes (spaces) A, B and C, where A should be adjacent to B, B adjacent to C and A should not be adjacent to C.

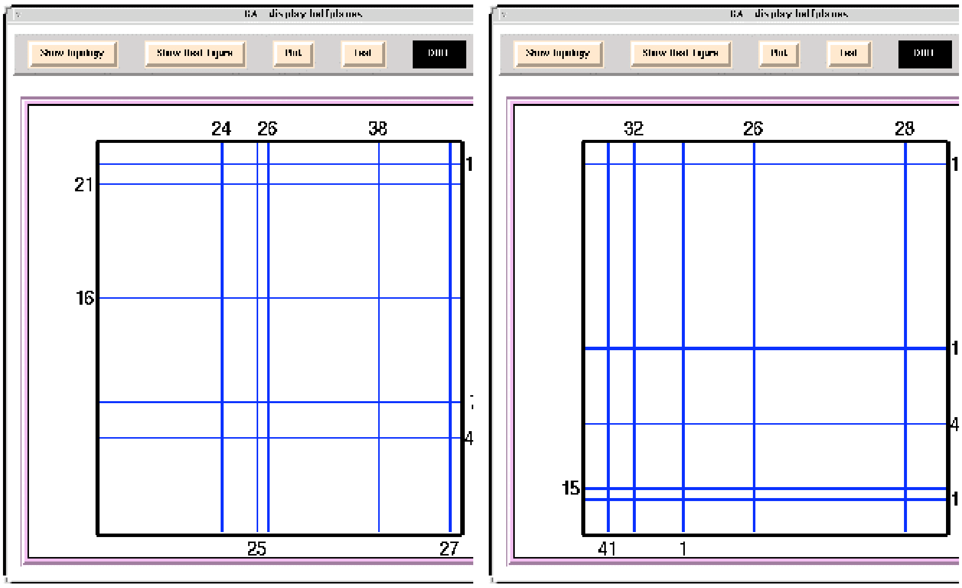
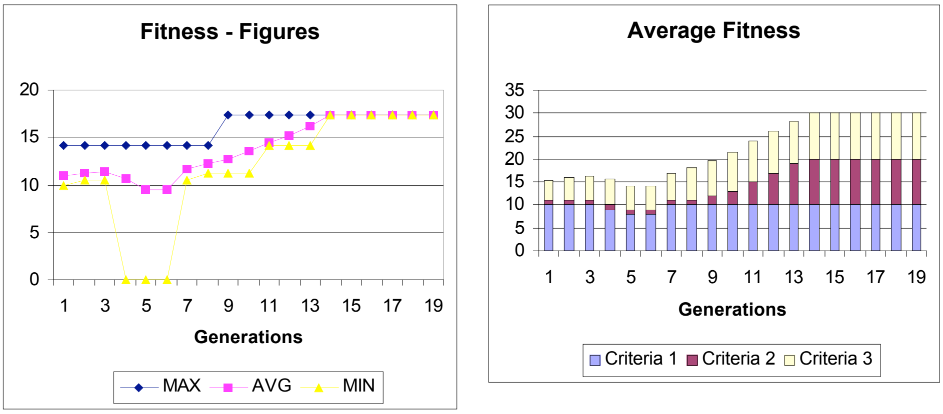


Figure 4: Examples of the halfplane arrangements

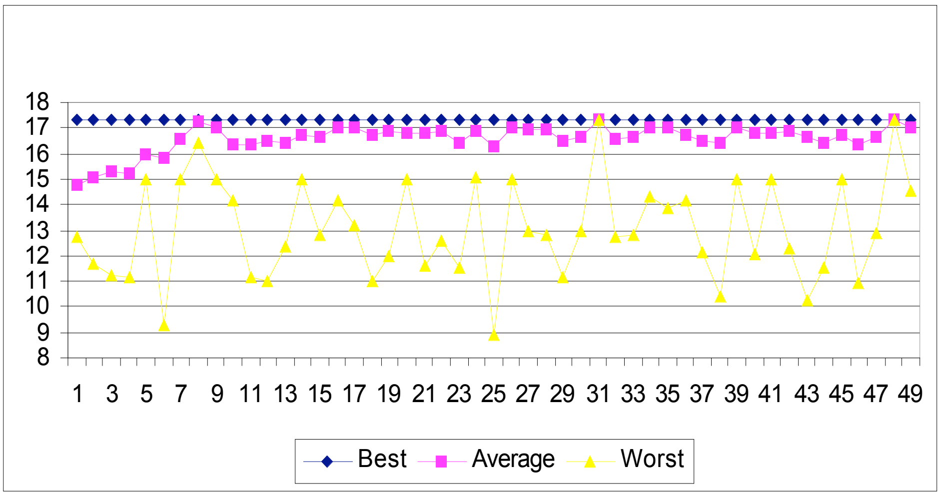
With these three criteria we use Pareto sets to calculate the best solutions and select randomly some of them to be evolved for the next generation. Figure 5(a) shows the result after 20 generations of best, average and worst cases in each generation. The value plotted is the "distance" of the gene. This distance is calculated as the square root of the sum of squares of each criterion. In Figure 5(b) the average value of each criterion is shown as the height of the bar chart. In this way it is possible to see the evolution of each criterion across the generations. In this case it simple to see that the shape connection criterion does not change much because we already generate shapes that are connected (they may be loosely connected after some generations. The criterion of shape overlapping is solved along with the top criterion, shape adjacency, across the generations. At the end of the evolution all layouts generated satisfied all the criteria.



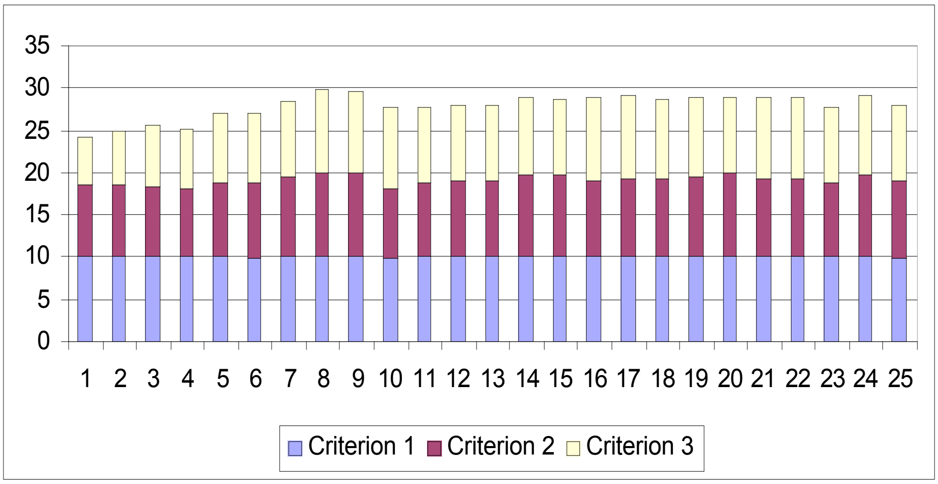
(a) (b)

Figure 5: Evolution of figures (layouts) (a) the distance of the best, average and worst cases (b) the average value of each criterion.

The final result of the evolution of the layouts is passed upwards for the particular halfplane arrangement used for this evolution. Once all the populations of one arrangement have been calculate it is possible to start to evolve arrangements in the same way layouts were evolved. The best two arrangements are selected and the crossover operation applied on them. The two worst solutions are removed from the population. Figure 6(a) shows the "distance" of the best, average and worst arrangement in the population for each generation. Figure 6(b) the average value of each criterion is shown as the height of the bar chart.



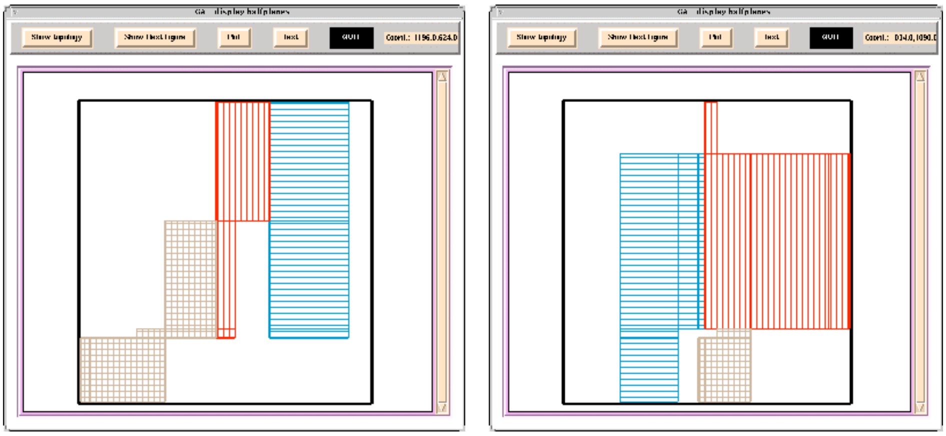
(a)



(b)

Figure 6: Evolution of the halfplane arrangements (a) the distance of the best, average and worst cases (b) the average value of each criterion.

Examples of the layouts produced after the evolution of figures in each halfplane arrangement is shown in Figure 7.



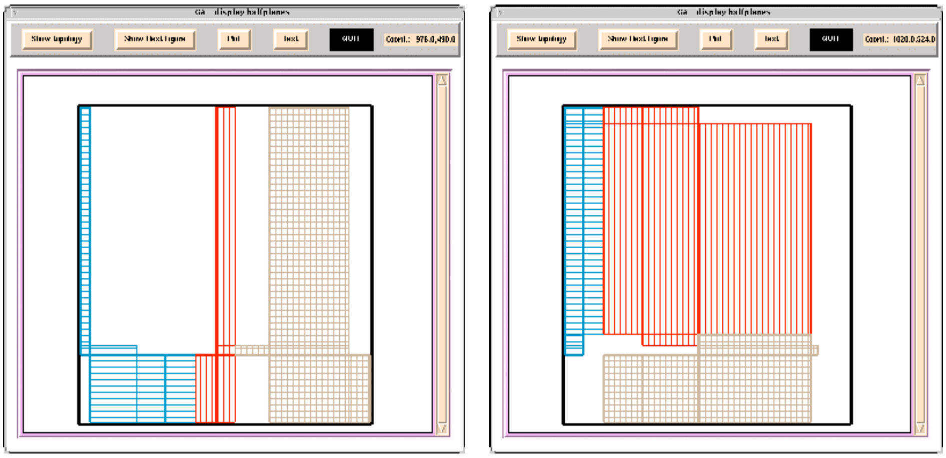


Figure 7: Examples of layouts generated.

The results of this system are listed below.

- layouts can be generated from a desired set of constraints.
- the output is not only a suitable layout, but a family of possible topologies (arrangements of halfplanes) from which such layouts can be generated. This allows the designer to have multiple views of the same solution.
- The system allows multiple criteria, so any additional topological and directional requirements can be expressed in the system.

6. Conclusions

This article presented an evolutionary system to generate space layouts. The layout specification is defined as a set of topological and directional constraints. While the halfplane representation is not limited to any type of boundary, the example shown in this article have straight and orthogonal boundaries (lines). This system completes the generation of legal topologies is the first of two stages in space layout planning. The second stage, that of dimensioning topologies is a well-known optimization problem with a variety of well-established techniques available for its solution.

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