SARTRE : A Computer Aided Design Tool for Robotized Production Lines

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Abstract

This article describes a tool for the design, the reconfiguration and the simulation of robotized production lines. SARTRE solves the problem of the allocation of spot welding points to parametrised robots. Each robot is characterised by a position in the space, a spot-welding tool and a type of kinematic.

The SARTRE resolution mechanism is split into two phases. An initial phase where a set of configurations for each robot of the line is generated. A robot configuration is composed of a domain of implantation and a domain of potential spot-welding tools. The system associates a subset of spot-welding points to each configuration and ensures that the robot in such configuration can access each point of the subset. A secondary phase in which the robots are allocated points. For each robot the system assigns an eligible configuration and tries to allocate all the points to the robots whilst respecting technical and geometrical constraints and optimising a cost function.

SARTRE has been developed with the Ilog SOLVER constraint library and the GUI generator Masaï.

Keywords : Constraint programming, Robotic CAD simulation, flexibility, resource allocation, design, reconfiguration.

1 Introduction

Adapting supply to demand is one of the vital challenges for the industries of mass production. It requires an increased flexibility of the production system. In the automobile industry this necessity has resulted in the construction of highly automated production lines capable of producing simultaneously several different types of vehicles. The design, or the adaptation to new products of an existing automated assembly line demands very complex preliminary studies to determine :

- the partition of welding points among the different robot stations ;
- the welding tools of every robot station ;
- the impact of the eventual addition of automatic tool changers ;
- that every robots work can be performed within the limits of its movements whilst respecting a given production time cycle and without entering in collision with its environment ;
- and finally that the line is globally balanced to assure an optimal charge on every robot station.

The only tools available at the eve of this study were a class of simulation systems for the computer assisted design (CAD) of robot stations [DOM87,DOM88]. These application programs are relatively well adapted to the study of the local flexibility of a given robot cell. They correctly solve the following type of problem: given a robot, an environment and a sequence of operations to perform by this robot, select the articulations and schedule the operations such that the operations may be accomplished in a given time without collision.

Whilst these facilities are necessary in the computer assisted design of production lines, they are not sufficient. In production line design it is essential to be able to study the possible assignments of welding operations to different robots. So CAD tools for production lines must allow both global and local design choices to successfully resolve the problems of the division of the manufacturing tasks, the choice of robotic material, load balancing and suboptimal production. These problems are not handled by present systems.

The addition of these features in a CAD tool necessitates the capacity to solve highly combinatorial resource allocation problems. This article presents the CAD production line tool, SARTRE. The plan of the article is the following. We expose the issues of production line conception. Then we present the SARTRE system, concentrating on the resolution of the allocation of spot welding points to parametrised robots and the constraint based resolution techniques used in particular. Finally we present an evaluation of the system and our conclusions.

2 Production line design

The central problem in the design of flexible production lines is the choice of a set of manufacturing tools, the configuration parameters for these tools and the division of the set of fabrication tasks among these tools. In the automobile industry, the production lines assemble the bodywork of different cars and the robots realise welding operations. Configuration parameters of an automatic welding tool are for example : the robot's position, the robot's kinematics articulations available or the robot's welding tool options for the different products to be fabricated in the particular production facility. An acceptable production line design solution must therefore establish a relation between the set of tasks and a set of correctly configured robots, whilst respecting the constraints of the production line and optimising its quality.

Yvars in [YVA92] formalised the production line design problem as finding an injection between a set of resources and a set of operations. That is given a set of operations, OP={OP1,...,OPn} and a set of available robots, R={R1,...,Rm}, find an injection between the set of robots and the set of operations, which respects the constraints imposed by :

- the physical position of the robot ;
- the local geometry of each assembly task ;
- the parameters of each tool (arm length, width, etc.) ;
- the production time cycle ;
- minor modifications of the production line are respected ;
- the robot can reach the welding points ;
- the priority and compatibility between standard robot pieces ;
- the welding pincers can reach a local welding point without colliding with the environment ;
- the welding pincers satisfy the technological requirements ;
- the maintenance of the production capacity of existing vehicles when reconfiguring a production line ;
- the production line load balance is optimal.

The production line design in figure 1 assigns the operations OP1 to OP10 to robots R1, R2 and R3

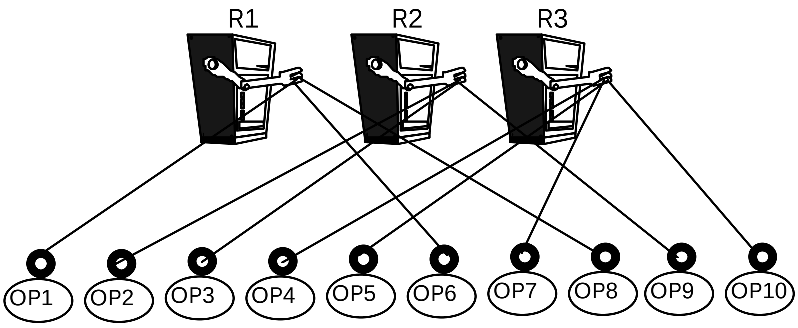


Figure 1 : A production line design

3 The SARTRE System

The SARTRE system is composed of several different elements including data bases, various CAD tools and numerical analysis procedures. In this article, however, we will concentrate on the module which solves the problem of the allocation spot welding points to parametrised robots whilst respecting the various production line constraints. Certain of these constraints necessitate algorithms with a very high computational complexity and are clearly ill adapted for constraint propagation. In fact some of these procedures use computationally intensive numerical analysis procedures. The originality of SARTRE is to divide the resolution of the allocation problem into two phases. An initial phase where a set of configurations for each robot of the line is generated. A robot configuration is composed of a domain of implantation and a domain of potential spot-welding tools. The system associates a subset of spot-welding points to each configuration and ensures that the robot in such configuration can access each point of the subset. A secondary phase in which the robots are allocated points. For each robot the system assigns an eligible configuration and tries to allocate all the points to the robots whilst respecting technical and geometrical constraints and optimising a cost function.

3.1 Initialisation phase

The initial phase of the SARTRE system effectively renders the search space of the problem discrete by the construction of a vector of possible parameters for each robot. The vector of parameters contains information about possible robot configurations (position, geometric and technical parameters, etc.). For each of the robot configurations the subset of possible tasks is determined, such that for any two robots and for any two configurations the two robots cannot collide. This computation is performed using algorithms developed at PSA Peugeot Citroën. The algorithms model at very fine level of granularity the robot production process and exploit PSA Peugeot Citroën's considerable know-how in robot-manufacturing. These algorithms are computationally expensive, but this phase is required only once per design study. Figure 2 illustrates the vector of parameters of a robot R1, which has five possible configurations, allowing it to attain fourteen different welding operations.

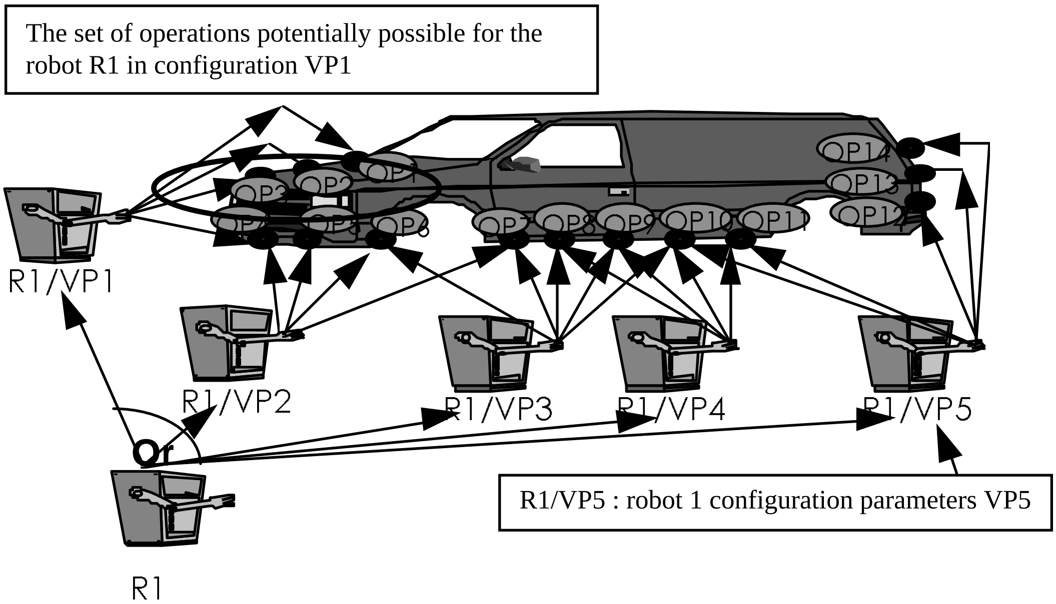


Figure 2 : The Configuration Parameters of Robot R1

3.2 **Constraint solving phase**

Once the initial phase is finished SARTRE must determine :

– a configuration vector for each robot ;
– a set of operations for each robot among those that the robot can realise ;
– optimise the production line for a given multi-criteria cost function.

This problem is equivalent to finding a partition of the set of operations OP into N subsets E1...EN, where each subset Ei represents the set of operations to be performed by a robot Ri.

$$\mathbf{E1 \cup ... \cup EN = OP \text{ and if } opi \in Ei \text{ and } opi \in Ej \text{ then } i = j}.$$

The first version of this module was developed in Le-Lisp (YVA90), using an *ad-hoc* resolution mechanism. This approach allowed us to test different ideas and heuristics which have been reused in the current constraint based version. The current system can allocate the robot resources required for problems with 10 robots, 250 welding points, 100 possible robot parameters and where the number of operations possible for a robot is not greater than 58. The size of the solution space is the number of possible partitions of set of the operations among the set of robots. In our case this is of the order of 10^250. When dealing with a solution space of this size it is useful to look for ways to represent the problem which will diminish the size of the solution space and increase the early cutting of the search tree.

3.2.1 **Problem modelling**

After several different tests, we chose a dual representation of the problem. In the first representation, each robot is represented by a robot object with a SOLVER variable for the possible configurations of the robot and a SOLVER set variable for the set of welding operations performed by the robot. In the second representation, each operation has an associated operation object with a SOLVER variable for the robot performing the operation. The advantage of combining two representations of the problem is that constraints may be formulated in terms of the robots or of operations. Figure 3 illustrates the objects of the problem model and the constraints that ensure the coherence of the objects of the problem model.

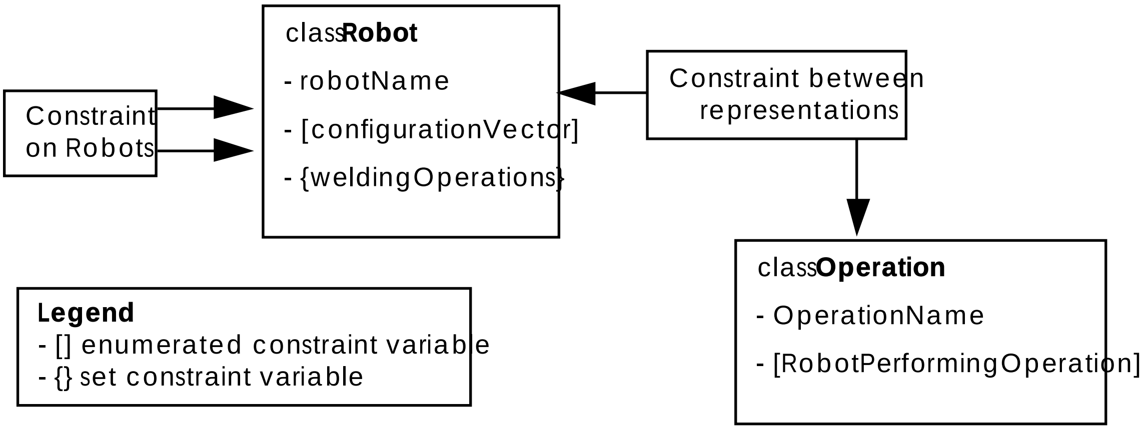


Figure 3 : The Problem Model

3.2.2 **Configuration Constraints**

The configuration constraints ensure the coherence of the relation between the two representations, that is between the operations to be performed and the robots. Thus if a given configuration is excluded for a given robot all the operations which can only be performed by this configuration are excluded from the robot's possible operations assignments. Let VPi={VPi1,...,VPin} be the set of configuration parameters vectors for robot Ri and OP(VPij) the operations to be performed by the robot Ri associated with the vector VPij then the following constraint is always true.

- **for all opk∈ Ei there exists a configuration VPij for Ri such that opk∈ OP(VPij) .**

3.2.3 **Operation partition constraints**

Certain sets of tasks must be performed by the same robot. This constraint is defined dynamically by the user. If W is a set of the operations that must be performed by the robot i and Ei the set of operations that may be allocated to the robot i then the constraint that the robot i must perform the set of operations W is written :

$$\mathbf{W \subseteq Ei}$$

3.2.4 **Robot Capacity Constraints**

This constraint imposes the minimum number of operations that a robot must realise and fixes the maximum number of operations that a robot can realise. If mini and maxi are respectively the minimum and maximum number of operations that the robot i can perform and Ei is the set of operations of the robot i, then constraint can be written as follows :

mini ² cardinality(Ei) ² maxi

3.2.5 Optimisation

There are several interesting criteria to consider when optimising a production line. Clearly minimising the cost of the robots (**RobotCost)** required to realise the operations is important. However, we also wish to minimise the time required by the robots to perform their given operations (**RobotTime)** in the solution. We chose to measure this criterion as the volume of the largest sphere that contains all the operations that the robot must perform. This is a good measure of the time to perfom the operations because when a robot's operations are close then the displacement time of the robot arm between operations is small. We chose to present the global optimisation cost function as a weighted sum of the two cost functions. The weight (**C)** as well as an additional coefficient (**k**), may be altered by the user to determine the relative importance to accord to the different criteria. Thus the user has the possibility of adapting the optimisation for a given study. The cost function for the problem can be written as follows :

Cost = k x RobotCost + (1-k) x RobotTime x C

The optimisation process uses a branch and bound procedure to progressively search increasingly better solutions. In this application the branch and bound procedure supplied in the SOLVER tool is optimised to explore the search tree from the precedent choice point after a solution has been found rather than re-exploring the entire search tree. A time-out mechanism has also been included in the search procedure.

3.2.6 Search Heuristics

The search problem consists of assigning a robot to each operation. The heuristic used in the current resource planning system is composed of two parts, the choice of the operation that will be assigned and the value (robot) that the operation will be assigned. The current system always tries to assign the operation which can be performed by the least number of robot configurations first. There are several possible strategies to select the robot to assign to the selected operation. Actually three strategies are available, each of these strategies has a different objective. The first strategy aims to balance the charge among the robots, the second strategy aims to minimise the volume of the sphere which contains the operations to be performed and the final strategy minimises the sum of the Euclidean distances between the robot and the welding operations. The choice of the strategy is determined by the user.

3.2.7 Over Constrained system

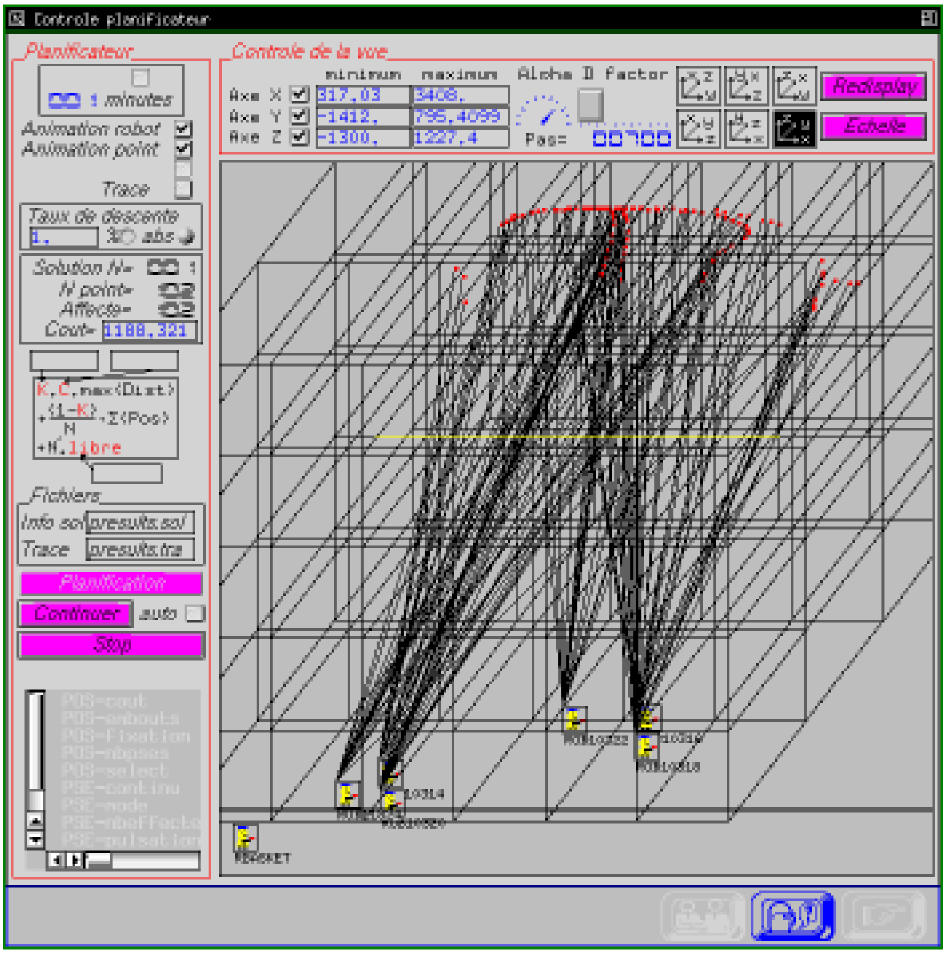
Very often the system of constraints that a production line must respect is insatisfiable. In this case, it is desirable to present a degraded solution. In the SARTRE system this is modelled as a virtual robot having the capacity to perform all the operations. Any of the operations that can not be performed by the real robots are automatically transferred to the virtual robot. In order to minimise the use of this robot a supplementary criteria (**p x Operations)** is added to the cost function to represents the cost of using the resource for an operation. The new cost function is thus :

Cost = k x RobotCost + (1-k) x RobotTime + p x Operations

Note that the technique of introducing a virtual robot can also be seen as a limited form of explication (abduction).

3.3 User Interface

The solution generated by the resource allocation unit are presented to the user in the form of a 3D graphic, which is commonly used in vehicle production line design. Figure 5 is a screen dump from the current system for the design of a production line of 6 robots.



3.4 Implementation

SARTRE has been developed on Sun work station under UNIX. It is implemented in Le-Lisp (CHA 91) and an adapted version of its object oriented level. All the modelling tools used are written in Le-Lisp ; the heart of the planning system is written in SOLVER (PEC92). The graphic interface is generated by the graphic interface generator AIDA (AID92) via the workshop MASAI. The robot positioning procedures are written in C. The parts of the SARTRE linked to the CAD tool CATIA (DAS92) of Dassault systems use Fortran77 in addition to CATIA's proper interface development tool. There is an additional link with the tools CADDS4X and Cimstation (CAD robot under computer vision).

4 Evaluation

An initial study was undertaken to validate the correctness of the resolution techniques used in SARTRE. The system was initially tested in a study of the introduction of a vehicle in a zone of a PSA production line. The direction of central studies and methods of PSA provided the data which represented about 200 welding points to be distributed among 12 robots. The system successfully partitioned the welding points among the robots. The solutions generated by SARTRE were tested by CAD robot simulation tools and proved to be correct. As a consequence of this study the configurations of the robots were modified.

The prototype was then tested on two other types of applications on different sites. The first application was the introduction of a new vehicle on an assembly line in the presence of existing products. This study was performed on three zones of a polyvalent production line, with about 500 to 600 welding points for half a vehicle. The second application was to study the design of a section of the production line as a function of the vehicle to assemble. The SARTRE system successfully generated : the dimensions of the zone, the positions and the pincer definition for each robot, as well as the distribution of welding points. SARTRE has also been used to do *a posterior* studies of the introduction of new vehicles on existing production lines, it has shown that significant gains can be made in the exploitation of site production resources.

The current system, with test data of the sizes given above finds an initial solution in less than two minutes on a SPARC2.

5 Conclusion and Perspectives

Version 1.5 of SARTRE is now used in all the studies of the design and / or reconfiguration of polyvalent production lines carried out by the Methods branch of PSA Peugeot Citroën. The current uses of SARTRE lead us to believe that important financial and temporal savings will be made in the design and optimisation of production lines, as well as in the reconfiguration of existing lines where the aim is to improve the exploitation of the site resources. SARTRE has also been used to study degraded solutions due to machine failures for example and to suggest alternative distributions of a range.

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