Single vehicle routing in reconfigurable manufacturing environments using the Bump-Surface concept

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Abstract

This paper presents a new approach for solving a generalization of the vehicle routing with pickup and delivery problem (VRPDP) for an automatic guided vehicle (AGV) moving in a 2D rapidly changing shop floor environment. Rabid changes are assumed to occur in the facilities layout of the shop floor, such as in the shape, size and location of (the obstacles) corridors, walls, machines, furniture, etc., as well as, changes in the positions of the pickup and delivery (P/D) stations. The problem to be faced is thereby a dual *NP*-hard combinatorial problem combining the characteristics and constraints of a motion planning problem (MPP) and VRPDP. The objective is to determine the optimum (minimum length) collision-free vehicle tour through all the P/D stations passing from each one of them exactly once. The proposed approach consists of two main phases: first, the Bump-Surface concept is used to represent the 2D manufacturing environment by a 2D B-Spline surface embedded in 3D Euclidean space. Then, the generated surface is being searched for an optimum vehicle route (satisfying the above mentioned constraints) using a genetic algorithm. The performance of the proposed approach is investigated and discussed through simulated experiments.

Keywords: Vehicle routing, motion planning, task scheduling, reconfigurable environment

1. Introduction

In the past, manufacturing systems were configured once for a stable environment. But now days, manufactures face a turbulent environment because the customers expect models/products not only with high quality but also with personalized features and shorter delivery [1]. Manufactures therefore have to be adaptable to it's permanently changing environment. This means that, manufactures have to be able to configure their environments continuously. Reconfigurable Manufacturing systems (RM) has been recently introduced [2] as an innovative direction of research and development towards with customized manufacturing. A RM system is designed for rapid adjustment of production capacity and functionality in response to new market conditions and new process technology. It has several distinct characteristics including modularity, integrability, customisation, convertibility and diagnosability. There are a number of key interrelated technologies that should be developed and implemented to achieve these characteristics. To that purpose, this work considers an RM approach that addresses the problem of how to construct optimum routings for the vehicles (AGV, mobile robots) in a shop floor that safely serves various pickup and delivery (P/D) stations.

In the single-vehicle routing with pickup and delivery problem (SVRPDP), a vehicle with a given capacity must serve a set of P/D stations by visiting each one of them exactly once and performing at each visit a task of pickup and delivery. The goal is to determine a tour through the stations having the shortest possible length while the total load carried by the vehicle never exceeds its capacity. The problem has several practical applications in real-life, e.g., in beer or soft drinks delivery where full bottles must be delivered while possible empty bottles must be collected and stored back into the vehicle; and in the transportation of underprivileged children from home to vacation locations [3]. However, when SVRPDP is considered in the shop floor things are harder. In particular, the planner must not only decide about the minimum in length tour through all P/D stations but also must guarantee that this tour is safe, i.e., collision-free.

SVRPDP is known to be *NP*-hard [4]. From the other site, motion planning problem (MPP) (i.e., the problem of determining a continuous, collision-free motion for a vehicle from a start to a desired goal position) is also an *NP*-complete and PSPACE-hard problem [5]. Prior work on exact algorithmic development for the P/D problem (PDP) has focused either on the SVRPDP or PDPs with hard time windows (PDPHTW). Particularly, for the case of SVRPDP, Psaraftis [6] proposed the first exact algorithm based on dynamic programming. Kalantari et al. [7] developed a branch-and-bound algorithm for the SVRPDP, Fischetti and Toth [8] solved the problem by using an additive bounding approach in a branch-and-bound algorithm. Ruland and Rodin [9] presented an algorithm following a branch-and-bound scheme, in which lower bounds are computed by solving a linear program relaxation of the problem. Hermandez-Perez and Salazar-Gonzalez [10], addressed through a branch-and-cut algorithm a variation of the SVRPDP concerning the movement of one commodity from pickup stations to delivery stations instead of two products, one from a warehouse to the delivery stations and another from the pickup customers to the warehouse.

Psaraftis [11] presented a forward dynamic programming algorithm to solve the single-vehicle PDPHTW. Dumas et al. [12] developed a column generation solution procedure to optimally solve the PDPHTW with up to 55 customers using a single vehicle/robot. Their approach works well only under either restrictive capacity or time window constraints. Nanry and Barnes [13] presented a reactive tabu search approach [14] to solve the PDPHTW using three distinct move neighbourhoods that capitalize on the dominance of the precedence and coupling constraints. A hierarchical search methodology is used to dynamically alternate between neighbourhoods in order to negotiate different regions of the solutions space and adjust search trajectories.

MPP is fundamental and one of the most complex problems in Robotics [5]. A plethora of techniques have been proposed in the literature for solving various forms of MPP [15]. Bump-Surfaces are recently introduced by Azariadis and Aspragathos [16] in order to solve the MPP in 2D environments cluttered with obstacles having arbitrary shape, size and location. This method represents the entire robot environment through a single mathematical entity. The motion planning solution is searched on a higher-dimension bump surface in such a way that its inverse image into the initial robot environment satisfies the given objectives and constraints. Investigating an extension of the basic MPP, Nearchou [18] proposed a genetic algorithm (GA) to address a MPP in a graph for a mobile robot, which during its motion performs a pick-and-carry loads operation. The proposed GA was used to optimize several task-oriented criteria and found superior (in regard to the quality of the solutions obtained) and faster than simulated annealing and hill climbing based heuristics.

The theme of the current study is to develop a new approach that faces the SVRPDP in a reconfigurable (changing) shop floor environment. By the term 'reconfigurable' we mean that the facilities layout in the shop floor can change rapidly according to the demands of production. It is worth pointing out that, in our scenario, the shop floor facilities constitute physical obstacles (e.g. corridors, walls, machines, furniture) for the vehicle. These obstacles can have arbitrary shape, size and location. Furthermore, following the same assumptions the positions of the P/D stations in the shop floor can change rapidly.

The proposed approach is based on an extension of the concept of Bump-Surface. In particular, using the Bump-Surface concept the vehicle's environment is represented by a 2D B-Spline surface in $\Re^3$ which is able to capture both the free space and the forbidden areas of the shop floor. A global combinatorial optimization problem is then solved on the resulted surface in order to determine the motion of the vehicle. The overall optimization problem is clearly intractable and therefore the right way to proceed is through the use of heuristics; hence, for this reason, it was decided to solve the problem using a GA.

The main advantage of our approach concerns the determination of the optimum sequence of the task-points while simultaneously computes an optimum collision free tour which connects the P/D stations and the depot. Unlike other methods that are limited to find only the optimum sequence of the task-points while they use a predetermined network of straight routes/rails which connect the P/D stations and the depot, our method is more flexible to compute smooth tours.

2. Problem Statement

Assume a vehicle, which is modeled as a point moving in a 2D manufacturing environment cluttered with obstacles with arbitrary shape, size and location and with a set of N P/D stations. The N P/D stations in the shop floor are served by a vehicle with capacity Q. The vehicle always starts and terminates its travel at an origin station or depot. At each P/D station the vehicle must perform a task of pickup and/or delivery. Each P/D station is associated with two quantities: a delivery quantity $d_i \geq 0$ and a pickup quantity $p_i \geq 0$, $i = 0,1,\ldots,N$. In addition, the shop floor can be reconfigured ((re)-configuration of the facility layout, i.e., changes on the P/D and the machines positions, new corridors for the vehicles on the shop floor, new walls, other equipment) in order to deal with customized production planning and scheduling. The aim is to compute a tour which satisfies the following criterion:

C1. To determine a feasible tour of minimum length staring and ending at the depot and serving all the P/D stations each one exactly once.

A feasible tour is one that first does not collide with the obstacles (walls, machines, other equipment) in the factory's facility layout, and second the total load along the tour never exceeds the vehicle's capacity Q. To ensure feasibility we further assume that $P = \sum p_i \leq Q$ and $D = \sum d_i \leq Q$. If a station requires both delivery and pickup, the two operations must not be serviced separately, and the delivery operation is assumed to be performed first.

3. The Bump-Surface construction

Given a 2D manufacturing environment the construction of the Bump-Surface is derived after applying the Z-value algorithm (see [16]). This algorithm considers that the environment is discretized into uniform subintervals along its *u* and *v* orthogonal directions respectively, forming a grid of points $p_{mn} = (x_{mn}, y_{mn}, z_{mn}) \in [0,1]^3, 0 \leq m,n \leq M-1$ where M denotes the grid size. The z_{mn} coordinate of each grid point p_{mn} takes a value in the interval $(0,1]$ if the corresponding grid point lies inside an obstacle and a value 0 otherwise.

The Bump-Surface is represented by a tensor product B-Spline surface with uniform parameterization $\tilde{S} : [0,1]^2 \rightarrow [0,1]^3$,

$$\tilde{\mathbf{S}}(u,v) = \sum_{m=0}^{M-1}\sum_{n=0}^{M-1} M_{m,q}(u) M_{n,f}(v) p_{mn}, \quad 0 \leq u,v \leq 1 \tag{1}$$

where q, f denote the degree in the u,v directions of the Bump-Surface respectively, p_{mn} are the grid points and $M_{m,q}(u)$ and $M_{n,f}(v)$ are the basis functions. Intuitively, the Bump-Surface consists of "flat" areas where its third coordinate is zero, i.e., $S_z(u,v) = 0$ and "bump areas" where $S_z(u,v) \in [0,1]$ [16]. For simplicity, it is considered that the 2D shop floor environment is the actual parametric space of $\tilde{S}$. Therefore one is able to trace the vehicle's tour in the original 2D environment through a one-parametric curve, $\mathbf{S}(u(t), v(t))$, $t \in [0,1]$ lying on $\tilde{S}$. This fact provides the necessary motivation to perform a search for a feasible tour on $\tilde{S}$ in order to satisfy the aforementioned motion-planning criterion **C1**.

4. Motion planning with P/D (Task Scheduling)

Let a 2D manufacturing environment cluttered by a priori known static obstacles with arbitrary shape, size and location and with a set of N P/D stations. In addition, let the vehicle be a point moving in the parametric space $[0,1]^2$. All the feasible configurations of the vehicle are represented on the Bump-Surface $\tilde{S}$ through a family of one-parametric curves lying on $\tilde{S}$. In the present method we consider that the vehicle traces a tour $\tilde{C}(t)=(u(t),v(t))$ given as a first-degree B-Spline curve:

$$\tilde{C}(t)=\sum_{m=0}^{K-1} M_{m,q}(t)\tilde{p}_m,\ 0\le t\le 1 \qquad (2)$$

defined in the parametric space of $\tilde{S}$. Here, K is the number of control points $\tilde{p}_m \in [0,1]^2$, $M_{m,q}$ is the basis function. It must be noticed that, the number, K, of control points $\tilde{p}_m \in [0,1]^2$ is defined by the depot point plus the number of P/D stations plus the overall number, b, of $\tilde{g}_l \in [0,1]^2$, $l=1,...,b$ which are added between every two P/D stations. For example, if N=3 and b=6 then K=10 and between each pair of P/D stations we have two points $\tilde{g}_l \in [0,1]^2$. Our variation curve design is focused in the determination of the $K-N$ intermediate points $\tilde{g}_l \in [0,1]^2$ such that, the curve $\tilde{C}(t)$ satisfies the motion-planning criterion **C1**. The first and the last control point, namely $\tilde{p}_0$ and $\tilde{p}_K$ respectively, is the depot point thus $\tilde{p}_0 = \tilde{p}_{K-1}$. It is worth to notice that, the number b of intermediate points depends on the complexity and the difficulty of the environment. Using a large number of b a tour with a higher flexibility is derived but the computational time becomes too big. In the majority of the experiments we use 2 intermediate points between each pair of P/D stations.

Following the results applied in [16] a feasible tour that avoids the obstacles should be searched in the “flat” areas of the Bump-Surface. A tour that “climbs” the bumps of the Bump-Surface results to an invalid tour in initial environment that penetrates the obstacles. By construction, the arc length of $\tilde{C}(t)$ approximates the length of its image $\mathbf{S}(\mathbf{C}(t))$ on $\tilde{S}$, as long as $\tilde{C}(t)$ does not penetrate the obstacles. Therefore, it is reasonable to search for a “flat” tour on $\tilde{S}$ in order to satisfy the objective **C1**.

The arc length of the image of $\tilde{C}(t)$ onto $\tilde{S}$ is given by [17]:

$$L=\int_0^1 \sqrt{E(\frac{du}{dt})^2+2F\frac{du}{dt}\frac{dv}{dt}+G(\frac{dv}{dt})}dt \qquad (3)$$

where E, F and G are the quantities of the first fundamental forms of $\tilde{S}$.

In order to take into account that, each P/D station requires both delivery and pickup we incorporating the following constraint:

$$P-D\le Q \qquad (4)$$

Minimizing L (Eq. 3) with respect to the points $\tilde{g}_l \in [0,1]^2$, $l=1,...,b$ subject to the constraint of Eq. (4) leads to a tour that satisfies the objective **C1**.

Taking the above into consideration the final global optimization problem is written as:

$$\min_{g_l}(L) \qquad (5)$$

subject to the constraint of Eq. (4) and its minimization with respect to $\tilde{g}_l \in [0,1]^2$, $l=1,...,b$ leads to a tour which satisfies the objective **C1**.

5. Computing the optimum vehicle tour

Equation (5) corresponds to a nonlinear optimization problem with nonlinear constraints. We propose the use of GAs [19] to solve the aforementioned problem because of their ability to search exhaustively large and complex spaces, reaching a global near-optimal solution in the presence of multiple loca minima.

The first step in applying GA is the choice of an appropriate representation to encode the possible solutions of the current optimization problem. Here, a mixed integer and floating-point representation was chosen. Each chromosome represents a possible tour for the vehicle as a sequence of the N P/D stations (including the depot) and the unknown $\tilde{g}_l \in [0,1]^2$, $l=1,...,b$ defining the B-Spline curve $\tilde{C}(t)$. The first part of the chromosome composed of N integer numbers, representing the sequence with which the vehicle reaches the N task-points. The second part of the chromosome composed of b floating numbers, representing the vehicle’s intermediate points between two successive task-points. In addition, the proposed GA has the following features being adopted after extended experimentation: parent chromosomes are selected for reproduction using the roulette wheel technique, mutation is performed using a boundary mutation operator, while crossover is performed as in the following: OX crossover is applied on the first part of the chromosome containing the integers, and one-point crossover is applied on the second part of the chromosome containing the floating-point numbers.

The main objective is to minimize *L* (see Eq. 5); therefore, fitness function was defined as,

$$F = \begin{cases} \frac{1}{L}, & if\ P - D \leq Q \\ 0, & otherwise \end{cases} \quad (6)$$

6. Experimental results

The performance of the proposed method is investigated for a vehicle moving in various 2D reconfigurable manufacturing environments cluttered with static obstacles, and containing multiple P/D stations. The results obtained indicated that the method always determines a near-optimal tour for the vehicle whenever it exists.

The overall method was implemented on a Pentium IV 3.2 GHz PC using Matlab. The grid size was set to 75x75, the number, of intermediate point was set equal to 2, *Q*=5. The appropriate values for the GA's control parameters were determined after exhaustive experimentation to be equal to: *population size*=100, *number of generation*=200, *probability of boundary mutation*=0.033 and *crossover rate*=0.75. Finally, in all experiments we set a_1 =0.7 and a_2 =0.3 in order to increase the importance of the first motion planning objective. In addition, a first-degree B-Spline curve was used to represent the vehicle's tour and a two-degree B-Spline surface to represent the Bump-Surface. Due the page limits, in the rest of this section only one characteristic experiment is presented and discussed.

Figure 1(a) shows a 2D shop floor environment cluttered with 10 polygonal obstacles. 6 P/D stations are assumed in the shop floor. Each P/D station is associated with two quantities: a delivery quantity $d_i \geq 0$ and a pickup quantity $p_i \geq 0$, $i = 0,1,\ldots,N$. In Fig. 1(a), the triangles represent the P/S stations and the black dot represents the depot point. Figure 1(b) shows the corresponding Bump-Surface. Figure 1(c) shows the computed feasible tour and the black dots represent the intermediate points.

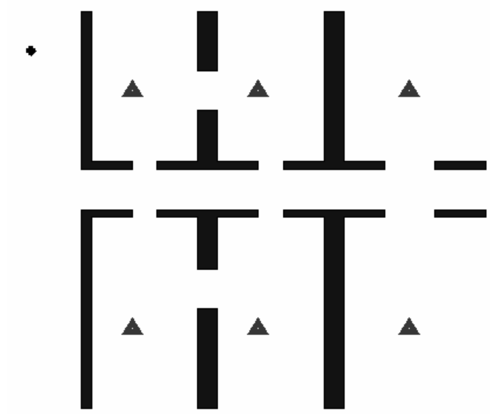

Fig. 1 (a). The initial 2D manufacturing shop floor.

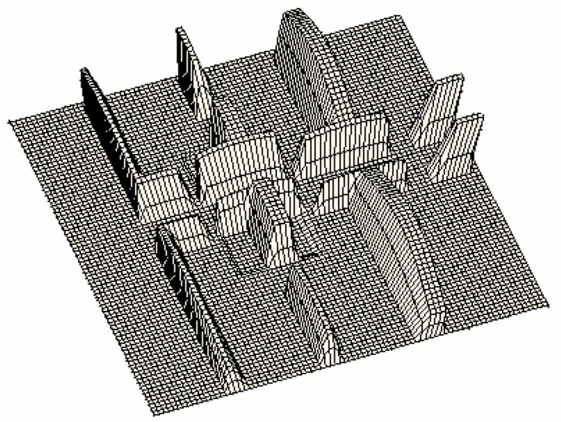

Fig. 1 (b). The corresponding Bump-Surface.

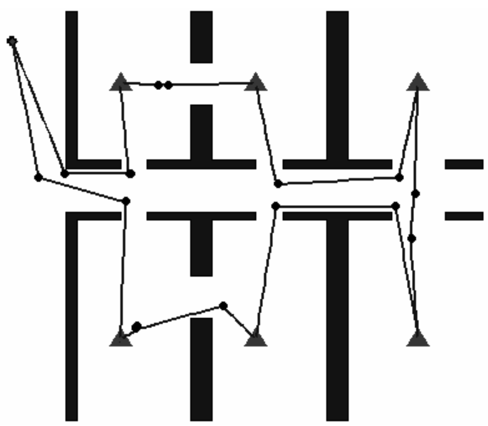

Fig. 1(c). The computed solution.

The above example concerns task scheduling problem in a 2D shop floor environment where the vehicle is requested to travel a long distance avoiding static obstacles and passing from each one of the P/D stations exactly once. The computed tour **C**(t) satisfies the motion-planning criterion **C1**. Although, using GAs it is not possible to guarantee that a valid solution tour will be obtained after each run, all our experiments have shown that typically we can get a near-optimum solution within the first or the second run.

7. Conclusions

In this paper, a new method for computing feasible vehicle's tours in the presence of 2D reconfigurable manufacturing environments has been proposed. The introduced method is based on the Bump-Surface concept. The computation of the feasible tour is performed on the Bump-Surface using a genetic algorithm.

Simulations have shown that the new method works effectively in complicated situations.

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