

Path planning for special robotic operations

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Abstract

The problem of robotic path planning has been the focus of countless investigations since the early works of the 70's and, despite the large number of results available in literature, is still a topic that draws a great interest. In virtually all robotic applications it is required to somehow define a feasible and safe path, and such a problem can be cast and solved in many ways, given the several possible combination of robots - industrial robots, Autonomous Guided Vehicles (AGVs), Unmanned Aerial Vehicles (UAVs), underwater vehicles - and scenarios - a production line, a warehouse, an hazardous mountain - and therefore a large number of approaches and solutions have been, and are being, investigated. The aim of this chapter is to provide an overview of such widespread literature, first by briefly recalling some classic and general-purpose methods used in path planning, then by focusing on some application-specific problems, related to AGVs in industry, medical robotics and robotic welding. This choice is motivated by the prominent relevance of the path planning problem in these three applications. Then, a single application of great industrial interest, such as robotic spray painting, is analyzed. Its specific features are described, and several techniques for task modeling and path planning are considered. A detailed comparison among these techniques is carried out, so as to highlight pros and cons of each one, and to provide a methodology to choose the most suitable one for the specific robotic spray painting application.

1 Path planning for general-purpose applications

Autonomous vehicles, mobile robots and, in general, robots, are usually required to move between two - or more - points in space, and solving the

This is a preprint of: Boscariol P., Gasparetto A., Scalera L. (2022)

Path planning for special robotic operations

In: Robot Design - From Theory to Service Applications. Giuseppe Carbone, Med Amine

Laribi (editors)

The final authenticated version is available online at:

https://link.springer.com/chapter/10.1007/978-3-031-11128-0_4

path planning problem results in the definition of a feasible and collision-free path to be followed by the robot. Additionally, some metric is usually embedded in the problem solution algorithm to fulfill the improvement of some performance criteria, with the aim of finding an 'optimal' solution. This problem is often intertwined with localization, i.e., the problem of understanding where the vehicle actually is [3], and map building [23], i.e., the definition of the map of an unstructured environment during the robot operation. Combining the two problems results in a Simultaneous Localization and Mapping (SLAM) problem [50, 11].

The extremely vast literature on path planning for mobile robots calls for a comprehensive classification of the several methods proposed over the years: one possibility is to classify the available methods among classical methods - such as roadmap planning or artificial potential field method -, heuristic methods - such as genetic algorithms, neural networks - and meta-heuristic methods, among which Ant Colony Optimization and Particle Swarm Optimization are worth of mentioning. A brief overview is presented here before focusing on more application-specific solutions.

1.1 Classical methods

Classical methods refer to the broad range of options that were developed before the introduction of artificial intelligence. The most authoritative references on such topics is the classic book [90], which focuses on roadmap planning, cell decomposition methods, and artificial potential field methods. Roadmap methods refers to a family of algorithms which share the capability of producing a map composed of one-dimensional curves: once the roadmap is built, the best option among the roadmap is chosen. In practical terms, usually the roadmap can be built as a visibility graph [100], i.e., a graph composed of lines that connect the vertices of the geometric representation of obstacles: the result is the shortest collision-free path, but such path is as close as possible to the obstacles [90]. If the goal is to move as far as possible from obstacles, Voronoi diagrams are a better method to build a roadmap: such diagrams are defined as the location in space which are equidistant from obstacles. The method based on Voronoi diagrams has found its use not only for mobile robots [49], but for UAVs [41] and underwater vehicles [22] as well.

The artificial potential field method was developed in the eighties [80] as a computationally efficient way to produce a collision-free path. The procedure is divided into two steps: the first one aims at defining a suitable number of potential field functions, that comprise both attractive and re-

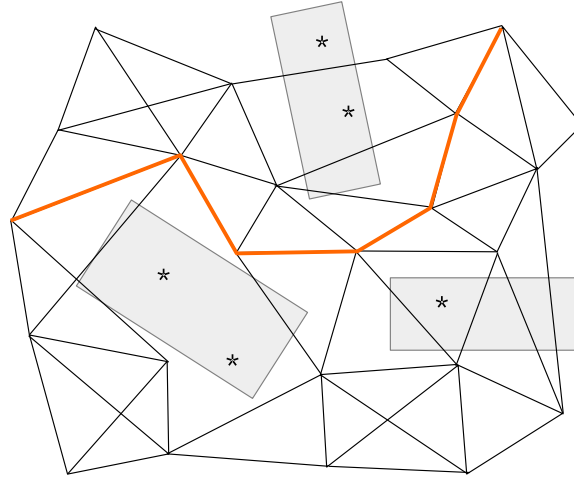


Figure 1: An example of probabilistic roadmap path planning.

pulsive fields. Attractive fields are used to drive the robot to its final goal, repulsive fields are used to represent the areas to be avoided, i.e., the obstacles: their sum produces a total potential that must be navigated to seek for an optimal path. Path optimization can be performed either in off-line or on-line fashion. The main strong point of this method lies in its conceptual simplicity, its main drawback is that the total potential field might exhibit local minima in which the robot might be trapped [121]. This difficulty can be however overcome by using navigation functions, i.e., by ensuring that the potential field does not have local minima [38] or by adding procedures to escape local minima.

Another classic method that is worth mentioning is the cell decomposition method [90, 95]. In this method a workspace with obstacles is split into regions, called cells. Each cell is numbered, and then translated into a node of a connectivity graph, which collects the information on the reachability of each node. The best sequence of cells that connects the initial and final cell is found by a simple graph search algorithm. The method can be applied to 2D spaces as well as to higher dimension spaces by simply adjusting the structure of the connectivity graph.

Further developments of the 'classic' algorithms have been achieved by introducing random sampling of the workspace, with the aim of boosting the efficiency for large-scale problems. One example is given by the probabilistic roadmap algorithm, which collects random points within the robot workspace, discards the one that overlap an obstacles, and tries to connect

the ones in the free space to produce a feasible path [79, 70]. Random sampling is also used in rapidly-expanding random trees [91]: in this method a tree structure is build by rooting it to the starting point of the path, then a growing algorithm tests the feasibility of a path built by adding 'branches' after testing the feasibility and measuring the progress towards the designated goal.

1.2 Heuristic and meta-heuristic methods

Heuristic methods have been developed since the 90's to circumvent the most common drawbacks sported by classic methods, mainly due to the low efficiency for large-scale problems and local minima trapping [101]. Heuristic methods mainly work by using 'shortcuts' to define a feasible solution, often sacrificing a complete exploration of the possible space of solutions, therefore they often trade off global optimality for speed.

Worth of mention is the use of Genetic Algorithms (GA), which have found an extremely wide field of applications, including path planning. Genetic algorithms work by representing a tentative solution to a general optimization problem by representing it as a population, whose evolution is dominated by selection (elimination of non-fit individuals), propagation of the genes to new generation and gene mutation. This method is of very general application, being suitable to the optimization of virtually every problem, with minimal effort on its mathematical representation, as explicit gradients are generally not needed. One of its main drawback is however, the possibility that a true optimal solution is not explored, and as such they are incapable of guaranteeing a global optimum. A basic implementation, as the one proposed, for example, in [1], associates a path, represented by a discrete set of point to be visited in sequence, with a chromosome. The initial, necessarily feasible, path, is then altered by creating a new generation, according to the crossover mechanism, followed by the evaluation of the fitness function to be minimized. The best chromosome are selected, to improve the quality of the population. This sequence is continued until reaching a pre-defined stopping criteria. Other early examples of application of GA to motion planning include [130, 154]. A path can be also generated by fuzzy logic, which works by combining several fuzzy rules, that take into account planning-specific goals such as proximity to the final goal, obstacle avoidance, and direction changes [159]. Alternatively, Particle Swarm Optimization (PSO) has found many applications in path planning: this technique is based on collecting the potential solution of an optimization problem into a swarm of particles. The solution evolves by exploiting the

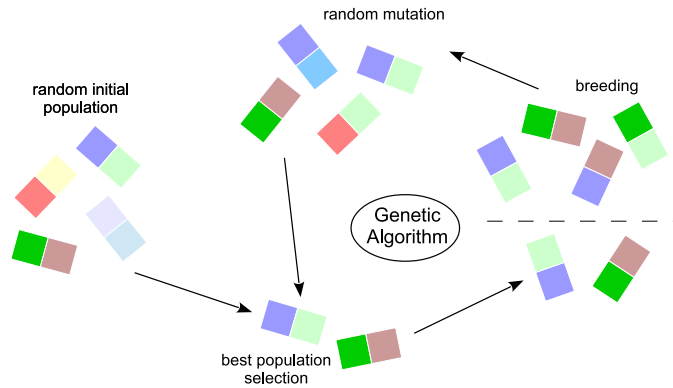


Figure 2: Graphical representation of a Genetic Algorithm optimization procedure.

activity of each individual element of the swarm, but as the algorithm progresses, the activity of each particle changes (i.e., it evolves) according to the experience gained by the whole swarm, combining the power of stochastic and evolutionary methods, and exploiting efficiently parallelism [148, 165].

Another popular biologically-inspired method is the Ant Colony Optimization (ACO) [54, 118, 151], which is a meta-heuristic and probabilistic method inspired by the attitude used by ants to forage food. Ants have the capability of finding the best path to a food source by relying on the traces of pheromones left by other ants. The optimization method somehow reflects this behavior, since the agents, in this case the artificial ants, explore the solution space and leave some long-term memory of the 'trail' run by each ant. The traced are then followed by other 'ants' by exploiting the results of the previous explorations, improving gradually the quality of the solution.

Ant colony optimization has found its first uses specifically in the field of path planning, being this the actual task performed by real ants. In a basic and typical implementations of a path planning method by Ant Colony Optimization [160], the representation of the navigable space is obtained by a grid map, which contains both free and forbidden grid elements. The task is to find the path from an initial point to the last one with a minimum number of turns and with the shortest possible path. Each ant follows a path that is built iteratively, and each move to another grid is defined by an heuristic that may vary with the implementation. Each ant then 'marks' the path depositing the so-called 'pheromone trace' - leaving an information on the 'fitness' of the path that is then used by other ants. Iterations are

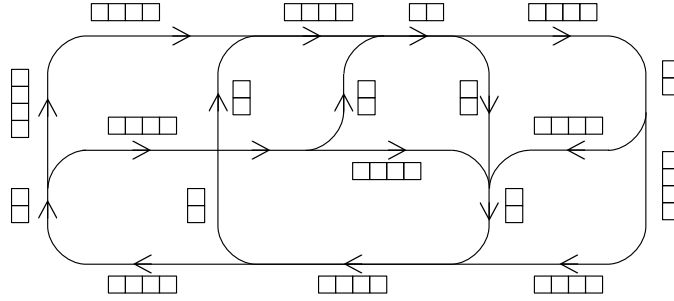


Figure 3: A simple route map for a small warehouse.

then stopped when reaching a pre-defined goal. Similar procedures can be applied to a graph, rather than a grid map with minimal alterations to the algorithm.

Similar to the Ant Colony is the Bee Colony method [39, 17], which combines a global search performed by 'scout bees', and a local search, performed by 'forager bees'. Furthermore, the Cuckoo Search Algorithm [107, 150, 133] is also experiencing some applications in the path planning of robotic systems.

2 Application-specific path planning

2.1 Path planning for Automated Guided Vehicles

Since their introduction in the mid fifties, Automated Guided Vehicles (AGVs) are an ever increasingly popular solution for material handling and all sort of transports in industry and logistic centers, as well as in transshipment systems [58]. Operating a fleet of AGVs requires to solve two issues: the scheduling and the routing problems. While the scheduling problem focuses on the definition of the time frame within which the AGV should move (respecting constraints such as priorities and deadlines), the routing problem focuses on the definition of the route, i.e., the path, that the AGV should move along. Despite being closely related, the two issues are often tackled separately [115]. Each of the problem can be technically challenging, especially when the complexity of the scenario is amplified by the numerosity of the fleet of AGVs, that in many cases can comprise several hundreds of vehicles.

Routing problems for AGVs, which are briefly reviewed here, are usually split into two groups, by separating static and dynamic routing problems. A

static routing problem solves once for all the target of defining, in advance, the route to go from point A to point B : if the same procedure is then applied to all possible combinations of two arbitrary points, a list of optimal paths can be defined and stored for later use. Once defined, the route between point A and B is always used. However, these methods are practical only for static scenarios, since every change in the working environment layout requires to re-compute the optimal paths. The most basic formulation of the routing problem is the well-known Traveling Salesman Problem (TSP), in which the distance to be covered for visiting a sequence of 'cities' and returning to the starting one must be minimized.

In response to the evident limitation posed by static routing problems, dynamic routing problems can be developed. Dynamic routing problems can adapt to time-changing conditions, such as layout changes or traffic [146].

In most cases, the routing problem focuses on defining shorter paths, as is the case of the early work [19]. In that work, the environment is described by a graph over which the quicker path is found by the classic Dijkstra's algorithm. Moreover, one of the first examples of conflict-free routing on a bi-directional path network is introduced in [40], which exploits a branch and bound algorithm. A method that is commonly used to reach a conflict-free situation is the use of time windows, as introduced in [81, 82]. In the time-window approach each node of the graphs holds the information of free time windows, and an arc connects only the nodes that are not busy by other scheduled jobs.

The literature has evolved over the years striving for computational efficiency and for larger scale scenarios, so the performance sported by the classic Dijkstra's algorithm has been boosted by switching to other search methods, such as the A* algorithm [147], the branch and price algorithm [123], as well as by using heuristic [103, 10, 87] and meta-heuristic approaches [139, 57, 131]. While most methods of path planning for AGVs use graphs to represent the path network, grids can be used as well, as in the case of the works [160, 157, 61].

The growing popularity of technology based on the Industry 4.0 paradigm is fostering a new stream of research on AGVs, being those a key element in a smart manufacturing environment with high automation level. Smart factories are required to face the challenges of flexibility and reconfigurability [89, 71], since currently a large part of the commissioning time of a plant is devoted to the generation of collision-free paths. As suggested by the Industry 4.0 paradigm [75], the challenges of decentralization, real-time capability, service orientation, and modularity are all to be faced by AGVs, which can be used in fleets of variable size, that can be coordinated either by

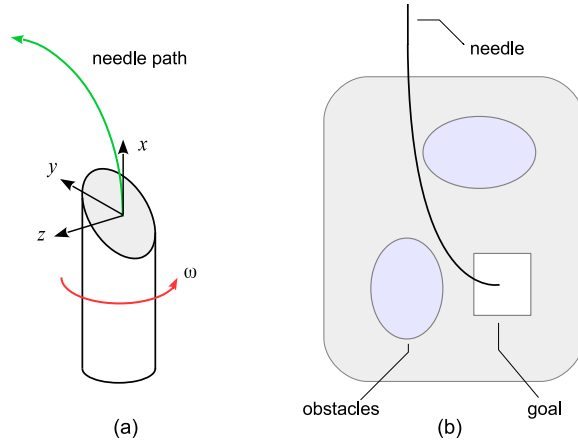


Figure 4: Steering needle: principle of operation (a), a typical insertion path (b).

a centralized system, or by exploiting the on-board sensing and computing capability of AGVs. The work [110], for example, proposes a neural-network based solution to the route-planning problem that is suitable to real-time applications and compliant with the limited computational capability of most AGVs.

2.2 Path planning for medical applications

The history of surgical robots is now more than 30 years old [21], and currently several medical tasks can be performed, with different shades of autonomy, with the aid of a robot. Common robot-assisted tasks include bone drilling and milling [98], laparoscopy [109] and stereotactic needle placement [88, 92] just to cite a few notable examples. Despite the quite long history of robotics, in general, and of surgical robotics, there are still several issues that need to be solved: one of them is how to fully exploit the capabilities of a surgical robot to their full extent to improve minimally invasive surgery.

One of the key tasks in surgery is needle insertion [52], which is a critical operation since it involves the interaction of a long and flexible element, the needle, with soft tissue, that must be performed with precision while providing minimal tissue damaging. Optimizing the needle-tissue interaction requires also to optimize the needle path: this topic is currently under investigation and thinner needles with a bevel tip, called steering needles [4] are being developed.

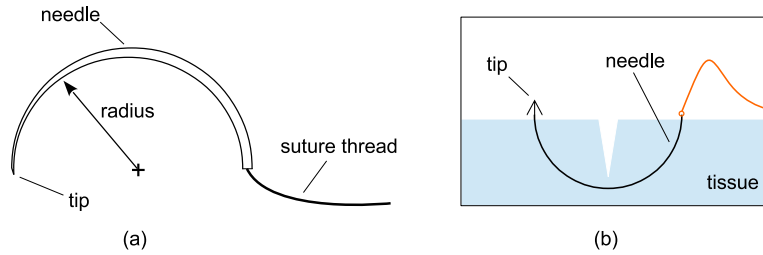


Figure 5: A suturing needle (a), a suturing operation (b).

When inserted in a patient's tissue, such needles follow an arc: by rotating the needle around its axis, a complex path composed by arc can be defined to reach the target area while avoiding obstacles. Since the needle is clearly not visible during the operation, its motion must be carefully planned ahead: in the work [155], a Rapidly-exploring Random Trees (RRTs) approach is used to perform this task, adding a backchaining mechanism to define the best needle entry point. RRTs are also used in [113], adding a reachability-guided sampling heuristic to alleviate the sensitivity of the algorithm to the choice of the distance metric. In the work [4], the optimal needle path is defined by dynamic programming, using simulations to optimize the performance in a feedback-loop approach. Iterative simulations have been used in [43], using a fast and gradient-free optimization routine that allows the algorithm to compute the optimal needle orientation and insertion point. Some other steering needle insertion planning methods are based on inverse kinematics of the needle, as in [48], but this method does not ensure solvability for all cases. Alternatively, the classic methods of Roadmaps [119] and Artificial Potential Field [46, 132] have been successfully applied, but such methods trade off the solution speed for global optimality [93]. More recently, also the Particle Swarm Optimization has been proposed as an effective tool for needle steering planning, as in the case of the work [20], showing that a good accuracy can be reached if a proper modeling of the needle-tissue interaction is developed.

Another surgical procedure that can be efficiently performed by robots is suturing, usually performed by specifically shaped needles to join together two tissues by means of a thread [78]. Suturing is a complex operation since its outcome depends on a large number of geometric parameters, such as insertion point, needle orientation, exit point. Moreover, several constraints must be taken into account, and a rather dexterous manipulator must be used. To cope with these difficulties, in the work [108] the path planning is

translated into an optimization problem using the A* solving method [42]. A general-purpose optimization, such as sequential convex optimization is used for the same task also in [126], which has showcased the first case of a fully autonomous stitching procedure, which however is executed at lower speed than the average surgeon. A sensible speedup is predicted in the work [143], in which the motion primitives are not defined a-priori, but they are taught to the robot by a human, showcasing a promising 'teaching by doing' application in surgery.

2.3 Path planning for robotic welding

The concurrent developments of welding technology and robotics has fostered a wide usage of welding robots in the manufacturing industry: the most popular and common example is found in the automotive industry. Welding robots have in many cases taken over traditional manual welding, which requires a skilled operator and exposes him to an hazardous environment [138]. The first step to the automation of robotic welding has been performed by introducing the on-line teaching method [45], which is also referred to as teaching and playback, since according to this paradigm the robot just repeats a process learnt after a human-guided teaching process. Such method is however not suited to any change of working conditions, which can significantly affect the outcome of the welding operation [28]. Manually teaching from a teaching pendant is also not suited to small production batches, so in all cases in which flexibility and accuracy are requested, or simply the complexity of the operation is too high, an off-line programming of the welding operation is requested.

Programming a robot for welding essentially requires to generate the welding passes, usually from data extracted from a CAD model, and then to generate the associated robot path [56]. The path is usually developed to enhance productivity, and therefore shorter (i.e., faster) paths are usually sought for, while ensuring obstacle avoidance, which can be obtained using some general-purpose methods [111].

However, welding requires to take into account some specific technical requirements, which mark the difference between general-purpose path planning and welding path planning. In the following, some of these features are recalled and some examples of the related literature are presented.

Joining metal bodies with large gaps requires multiple-pass welding, i.e., the joint must be created by carefully stacking the weld beads according to the best possible geometry. This problem is analyzed in [164], by developing an algorithm to produce optimal paths on the basis of an analytic model of

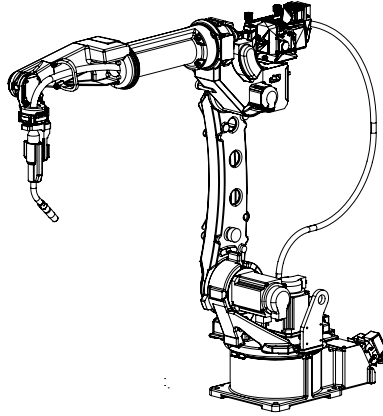


Figure 6: A six degrees-of-freedom soldering robot.

the bead deposition process. The planning of multiple-bead passes are investigated also in [2], in which the multiple bead passes are planned according to geometry data extracted from a CAD model, and then the transitions between passes are planned for collision-free motion using the A* algorithm. The minimization of the bead number for a faster operation is dealt with in [156], which again uses simple analytical descriptions of the bead geometry to produce optimized welding paths.

Another feature of robotic welding that affects path planning is functional redundancy, which arises from the symmetry of the welding torch. Such redundancy can be exploited, as done in the works [60, 74], to ensure task feasibility when coping with singularity avoidance and joint limits, or for fulfilling a secondary goal.

Another task-specific feature is welding weaving [36, 162]: traditionally it is obtained by adding an oscillating device between the robot flange and the welding torch, but such device is not required when weaving is introduced at the motion planning level, simply by adding a sinusoidal displacement to the end-effector path [96, 129].

A feature than should not be overlooked is that the heat generated during welding introduces some thermal-induced stresses on the material, causing its deformation [116]. The usual approach is to minimize the overall distortion by carefully sequencing the beads deposition [104], according to the solution of a scheduling optimization problem [84]. The solution to this scheduling problem is generally obtained through general-purpose optimization routines, among which genetic algorithms seems to be quite popular, as in [77, 76], usually defining the fitness function according to a FEM model

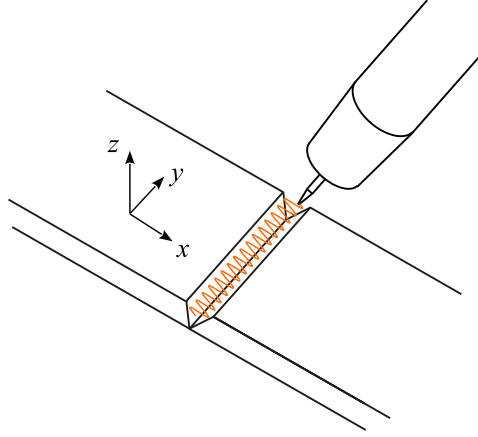


Figure 7: Weave bead welding of a V-groove: planned path.

of the thermal-induced distortions. Alternatively, some heuristics [83, 85] can be used in lieu of a thermo-mechanical model. Some other options for sequencing welding operations are the Ant Colony Optimization and the Particle Swarm Optimization [136, 15].

3 Path planning for spray painting robots

3.1 The problem of tool path generation

Nowadays, painting robots are employed in a large number of industrial and manufacturing applications, especially in the automotive, aircraft and furniture manufacturing sectors. The first painting robot was developed by the Norwegian company Tralffa in 1969, and was used for painting wheelbarrows [66]. Since then, the employment of painting machines has been rapidly increasing, thanks to the several advantages of using robots in a paint finishing system [13]. First of all, robots in automation allow to remove humans from hazardous environments, since spray paint particles, if inhaled, can be toxic, carcinogenic, and can lead to chronic neurological problems [97] and pulmonary dysfunctions [35]. Furthermore, the spray painting environment is usually noisy, and requires handling bulky paint guns, while performing repetitive tasks. Another feature of automatic painting is the consistency of the results, since a spray painting robot can ensure better performance in terms of repeatability of the resulting surface, paint uniformity and reliability, than the most skilled technician. Furthermore, robot manipulators



Figure 8: An industrial spray painting robot.

afford a greater level of system flexibility, allowing facilities to rapidly adapt to changes in the product design. Robotic painting systems ensure the optimization of cycle time and paint waste, and, as a consequence, a reduction of the amount of gaseous polluting emissions [26].

The tool path planning, i.e., the definition of the sequence of positions and orientations of the robot end-effector during the task to ensure a uniform paint distribution is still a challenge in robotic spray painting. Two main approaches can be adopted for the tool path planning: manual and automatic [24]. In the manual approach an operator manually moves the robot to each desired position, recording the internal joint coordinates corresponding to that end-effector pose [99]. In addition, operations such as activating a spray gun are specified as well. The program is then executed by the robot that moves through the recorded points. This method of robot programming is usually known as *teaching by showing* or *robot guiding*. Similarly, the positions and postures of the robot tool on the processing path against actual work-pieces can be defined by acting on the teaching pendant connected to the robot controller, or by using appropriate external teaching support devices, such as in [134]. Manual tool planning can be very time consuming, since the operators usually adopt a trial-and-error approach. With this approach the quality of the results, the cycle time and

the paint waist are strictly dependent on the experience and on the skills of the operators. Furthermore, during the execution of the teaching tests the normal production operations must be interrupted.

To overcome these problems, spray painting path and trajectories are usually generated automatically, with an approach called *Computer-Aided Tool path Planning* (CATP) [24]. This approach is based on the processing of a Computer-Aided Design (CAD) or a point cloud model of the part to be painted, and on the automatic computation of the path and trajectory that the painting robot has to follow. The automatic generation of tool paths avoids trial-and-error operations and reduces the time required to deploy a paint system for a new product, thus reducing production time and costs. However, automatic tool path planning is still a challenging task since the results of the painting process is heavily affected by complex and intertwined factors such as part geometry, the modeling of the spray paint deposition and the flow rate flux of the spray gun. All such information should be included to produce a proper definition of the painting application.

Another important aspect that must be taken into account in the automatic path planning is the compliance with kinematic and dynamic limits of the manipulator. A common approach is to decouple the path definition and the motion law planning into two separate problems [68]. In this way, the sequence of points that the tool has to follow are defined to ensure a proper covering of the target surface without a specific time law. The motion law, i.e., the speed and acceleration profiles, are then designed by taking into account the specifications and the limits of the manipulator.

In the context of robotic spray painting, recent researches include spray modeling and simulation [158], automatic path planning [112] and trajectory planning [141]. Furthermore, robot kinematic and dynamic control [106, 163], methods for optimizing the base position of mobile painting manipulators [120], as well as pose estimation systems [152] are currently being studied. The following subsection introduces the problem of spray painting modeling, which is a prerequisite for the subsequent definition of the path for the spray painting robot.

3.2 Spray painting modeling

Spray painting is a complex process, in which paint is transferred to the object surface for protection or aesthetic using air spray as an atomizing medium. Many factors affect the paint flow rate flux through the spray gun and the distribution of spray within the spray cone, which is generally non-uniform. In particular, the most relevant factors that have to be considered

are the technical features of the spray gun and paint nozzle, the air pressure, the amount of thinner in the paint, the temperature of paint and work-piece surface, and the paint viscosity. At present, the mechanism of spray painting is well understood and several models for the flow rate flux and the paint deposition process have been proposed and studied. Most of the paint deposition models consist of analytical functions, which parameters should be determined through fitting repeatable experimental data. These mathematical models usually describe the paint deposition rate on a flat plane with a static spray gun. To account for the painting robot trajectory, the paint thickness is obtained by integrating the paint deposition rate along the path of the spray gun.

Empirical paint deposition models offer a significant advantage over simulation results obtained with numerical methods that usually require complex formulations and high computational costs. Empirical models can also be incorporated into existing simulation tools, providing the user readily available information about the painting process and the characteristics of the resultant coverage path. The main purposes of a deposition model are to capture the structure of the deposition pattern that can be used in a planning system, and to support simulations used to evaluate potential path and trajectory planning algorithms. Indeed, paint deposition models are needed to determine the optimal inter-pass spacing for robotic spray painting, which are the basis of the path planning. These two requirements lead to contradictory criteria, since a deposition model should be accurate enough to predict the paint coverage on different surfaces, but, at the same time, should be mathematically simple and computationally light to be efficiently used within a path planning system. In the deposition process, with *paint coverage* it is usually indicated the total paint thickness on the surface, which depends on the rate of the paint deposition, on the path followed on the surface, and on the speed of the paint gun during the spraying task.

Early approaches to the modeling of spray painting use simplified deposition models, approximating the paint flux of the spray gun with simple analytical functions. These approaches are, in the majority of cases, limited to flat surfaces or make first-order approximations of the surface geometry. For this reason, the utility of these models for the simulation of reliable paint deposition remains limited and restricted to few real applications, such as planar surfaces of automobiles chassis.

Several analytical function are taken into account for the modeling of spray painting. A simple elliptical thickness distribution is considered in the deposition model presented in [135], a parabolic thickness profile with a circular deposition pattern is adopted in [128, 25, 32], whereas in [63] a

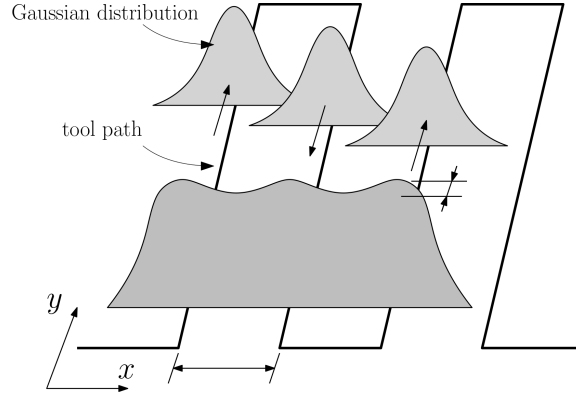


Figure 9: Gaussian paint deposition modeling: evaluation of paint thickness uniformity.

Gaussian distribution with elliptic cross-section is proposed.

Radially symmetric Gaussian distributions of color intensity within the spray cone are considered in the deposition models for decorative robotic spray painting in [124, 51, 144]. Other examples include the deposition model based on a bi-variate Cauchy distribution for the paint deposition applied to a flat panel presented by Ramabhadran and Antonio [117], and the model proposed by Balkan and Arikan, based on a beta distribution, which uses the shaping parameter β to take the flow-out of the paint into account [14, 122]. Furthermore, Hertling et al. propose in [73] a mathematical model for the paint flux field within the spray cone derived from experimental data on flat plates. Results indicate that deposition patterns are not uniform, and not parabolic, as reported by other researchers, but show a minimum at the center of the spray cone.

In the previously described researches the simplified mathematical formulations are developed for aerosol spray painting only. Nevertheless, nowadays, the modern automotive coating lines are increasingly installing electrostatic rotating bell (ESBR) atomizers, which allow one to obtain high transfer efficiency thanks to the potential difference between the rotating bell and the grounded surface to be painted [37, 53]. ESBR combine electrostatic and aerodynamic effects to spray the charged particles (with a typical diameter of 10-30 μm) to the target surface. Therefore, the mechanism of paint deposition are complex to be investigated and empirically validated analytic models are needed.

Conner et al. presented in [37] a paint deposition model that accounts

for the deposition pattern of ESRB atomizers and the effects of surface curvature. The deposition pattern is modeled with an asymmetric planar deposition function based on a set of Gaussians, which globally assumes the shape of an asymmetric volcano. The model is tested on primer coated Ford Excursion doors with good results, but presents some limitations in the predictions of paint deposition on highly curved surfaces. In this case, the paint deposition is under-estimated due to electrostatic effects that actually bend the trajectory of the paint droplets back to the edges of the surface.

A limitation of the analytical approach of paint deposition modeling is that sensible errors can be introduced when dealing with curved surfaces. This is due to the assumption that the streamlines of paint droplets are straight, unlike the real situation in which the streamlines are curved due to the effects of turbulence in the flow field or due to the shape of the work-piece [34]. The problem can be overcome by simulating the paint deposition process with a computational fluid dynamics (CFD) approach, which can precisely describe the flow field and take the turbulence effects into account [47, 59].

3.3 Path planning approaches

In the context of robotic spray painting, robot paths are frequently planned through self learning programming. The process can start from the CAD model of the work-piece to be painted, described by means of a parametric model, a tessellated mesh [128, 24, 167], or by a point-cloud model acquired by means of vision or proximity sensors [67, 152]. Several examples of path planning starting from CAD models can be found in the present literature. Early examples are given by [72], where a method for accurate simulation of robotic spray application using empirical parameterization is presented, and by [6], where the spray path is first automatically generated on the basis of the CAD data of the work-piece and the spraying parameters, and then converted into robot commands.

The simplest path planning approaches that solve the uniform coverage problem (i.e., to generate a spray path such that the entire surface is completely covered and receives an acceptably uniform layer of paint deposition) take into account single parametric surfaces and are based on the definition of an offset curve. In particular, a start curve (also termed seed curve [7]) is generated on the target surface, then the subsequent paths are built by offsetting the start curve along a family of curves orthogonal to initial one. This approach is implemented in [9], where the coverage trajectory generation problem is decomposed into three sub-problems: 1) selecting a seed

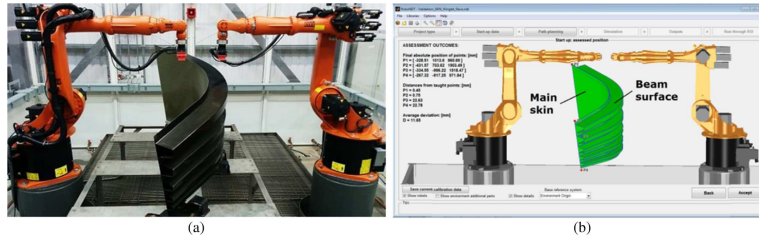


Figure 10: Spray painting application (a), automatic path generation software (b) (image taken from [105]).

curve, 2) determining a speed profile along each pass, and 3) selecting the spacing between consecutive passes.

The spray deposition can be applied continuously without stopping the paint flow or discontinuously by turning the tool on and off. Several path patterns can be created based on the start curve, such as zigzag, raster, and spiral [18, 24, 161].

If 3D surfaces are considered instead of planar ones, the path planning becomes more complex. A possible strategy is referred to as 'folding': a 3D model is virtually folded in 2D and treated as a single large surface, then paths are generated in 2D [73]. However, this method introduces higher errors as the surface curvature increases.

The path planning on 3D surfaces can also be solved by means of a feature-based approach: each part to be painted is treated through a set of simple features or elementary surface geometries such as planes, cylinders, cavities (regions with negative curvature) and ribs (parallel narrow regions with high curvature). The paths for the robot are then generated for these features individually using predefined strategies for each region [145]. Another example of path planning on typical regular surfaces including planes, cylindrical, conical and spherical surfaces can be found in [166]. The method is also extended to complex free surfaces with large curvature using hierarchical segmentation to divide the original surface in a number of regions to be planned by template programming. The authors in [86] present a general method of offset curve construction with tool-adaptive offsets for free-form surfaces. The offset path is obtained as a family of iso-curves of an anisotropic distance function of a seed curve on the workpiece surface. In [105] a mesh following technique for the generation of tool-paths directly from tessellated models is presented. The technique does not introduce any approximation and allows smoother and more accurate surface following tool-paths to be generated.

Surface segmentation is often used in robotic painting path planning when dealing with complex free-form shapes to divide them into simpler regions (patches). In [8] the authors showcase the segmentation of a complex automotive surfaces into topologically simple surfaces with a hierarchical procedure using the concept of the watershed segmentation of surfaces [114].

In [25, 128, 32, 33, 29, 31, 30] the authors adopt a multi-patch approach, in which a CAD model is firstly approximated by a large number of small triangles. The triangles with the nearest locations and directions are then combined into flat patches. For each patch, an approach for flat surface is applied to generate the paths. In [127] tool path planning approach which optimizes the tool motion performance and the thickness uniformity is presented. The method first partitions the part surface into flat patches based on the topology and normal directions, and then determines the movement pattern and the sweeping direction for each patch. Both zigzag and spiral patterns are considered. Zigzag patterns allow simple tool movement, but their non-isotropic nature introduces makes it difficult to achieve thickness uniformity near the patch borders. Spiral patterns have isotropic nature but they may lead to disconnected path segments for some patch shapes.

In [18] a multi-patch approach is considered, where mesh triangles are sorted to define tag points directly, without the need of sorting triangles into a flat or low-curvature patch. In this manner, the spraying path on complex products such as vehicle chassis can be planned. In [153] a surface segmentation based on the determination of the maximum deviation angle of the normal vectors of the vertexes is implemented to generate the patches that are connected and can be covered by paths uniformly. To minimize the cycle time and the material waste, the segmentation also considers as obstacles the holes and the unnecessary painting regions. Furthermore, in [64] a genetic algorithm for surface segmentation is presented and two methods are considered: the first is able to separate the largest patch from the surface, whereas the second is capable of dividing the surface with the smallest number of slices.

In [44], two main methods are identified for the offline path planning of 3D surfaces. In the first approach the CAD mesh file is generated and the robot path is planned by considering the mesh points and the normal vectors to the surface. In the second one, orthogonal planes are used to cut the surface to be coated so as to generate a series of scanning curves. The normal vector is calculated to define the orientation of the torch on every point of the curves. This method is also known as *cutting method* or *marching method* [12]. For example, in [62] radial basis functions are used for surface modeling, and the intersection of surfaces for high-precision

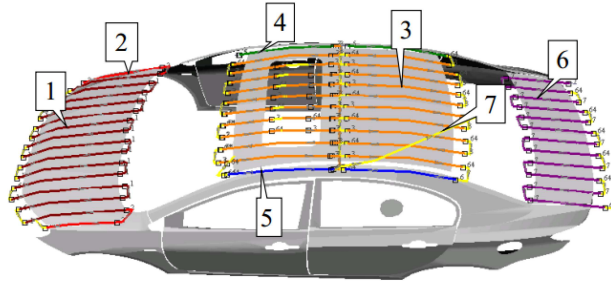


Figure 11: Spray painting paths on a car body (image taken from [29]).

trajectory generation. Furthermore, in [55] the cutting method is applied to ensure the uniformity of the distance of two neighbor scanning passes in thermal spraying.

Most of the previously referenced works are based on CAD models to plan the robot tool path. However, the path planning can also be based on point cloud models, obtained by means of vision systems or proximity sensors. In [149] a path planning approach based on point cloud slicing is presented. The authors propose an adaptive method to determine the direction of the slicing plane, use polynomial fitting and uniform interpolation method to obtain smooth spray paths, and introduce an iterative formula to optimize the interval between slicing planes.

Another example of path planning approach in which the model of the object to be painted is acquired through artificial vision is given by [67]. In this work, graph theory and operative search techniques are applied to provide a general and optimal solution to the path planning problem. In particular, the object to be painted is partitioned into primitives that can be represented by a graph and the Chinese Postman algorithm is run on the graph to obtain the minimum-length path covering all arcs.

More recently, in [152], an image of the target is captured using RGB-D vision sensors. The image is then segmented using a segmentation network and processed to estimate the relative pose between the actual target and the pre-scanned target model.

Besides CAD and point-cloud models, other approaches to automatic path planning for painting robots rely on the processing of digital images for artistic purposes. In this case, the path planning can be based on non-photorealistic rendering techniques [94, 65, 125, 16], which apply user defined algorithms to render an input image into an artwork, or on deep learning approaches that take an input map of a desired texture, and infer robotic

paint commands to produce that painting [51].

In most of the previous examples the robot path is planned offline. This is due to the fact that offline path planning allows optimization and repeatability of the robot operation, especially when the same task has to be repeated numerous times for many identical pieces, which is a common scenario in the industrial and manufacturing applications.

However, the offline path planning strategy can lead to a decreasing in the spray quality, for example if large-size elements prone to deformation, such as the hull of ships or parts of buildings, are considered. Indeed, in this case, gravity and mechanical deformation would result in inevitable deformations for large-scale parts and possible discrepancies between the as-built workpieces and their nominal specifications would arise [102]. Thus, the perpendicularity and constancy of distance between subsequent paths computed on the basis of nominal CAD models are not guaranteed, leading to decreased spray quality. Furthermore, in the case of workpiece conveying on the spray-painting pipeline, random pose changes of the part to be painted might occur. To overcome these problems, systems based on the usage of real-time 3-D reconstruction together with online and adaptive path planning techniques are developed. An example of online path planning is given by [27], where the authors adopt a visual feedback based on fringe pattern to control the motion of the robot tool in a closed loop to achieve paint film uniformity. Furthermore, the authors in [69] propose an online modeling approach for automatic spray-painting applications. Specifically, two consumer RGB-D cameras are mounted on the two sides of the pipeline, and the data streams of the moving workpiece are continuously collected for the subsequent trajectory planning. Another example of real-time path planning for spray painting purposes is given by [137], where a stereo camera is used for surface recording via a real-time, appearance-based mapping procedure, as well as to steer the painting robot. However, in the online path planning the difficulty on keeping the camera cleaned from paint arises, and more computational resources are needed with respect to the offline scenario to operate both the image acquisition and the path computation in real-time.

The problem of path planning in spray painting robots is usually decoupled from the definition of the motion law that the manipulator has to follow during the execution of the task. The main objective of the trajectory planning is to ensure constant tool speed to minimize the variation of accumulated film thickness on the surface [5]. An early example of optimization of the speed profile can be found in [117], where two constrained quadratic problems are considered to minimize the painting time subject to lower bounds of speed, and minimize the variation in coating thickness.

Nevertheless, these problems do not consider any limit on the end-effector acceleration or any upper bound on end-effector speed. More recently, in [30] not only the spray path defined on a Bezier triangular surface model, but also the end-effector speed along the specified path are optimized to ensure limited variation of the coating thickness.

In [140, 141, 142] the authors present a path-constrained trajectory planning strategy that provides feasible motion profiles without resorting to optimization routines and without the need of a dynamic description of the manipulator. The algorithm takes as input an arbitrary description of the end-effector path in the operative space and apply a sequence of look-ahead filtering operations on the speed profile to ensure end-effector speed and joint acceleration limitation.

4 Conclusions

In this chapter an overview of the literature on path planning generation in robotics has been presented. The centrality of the problem in robotics is testified by the large number of works written on the topic, which comprises both general-purpose planning methods and application-specific ones. The analysis has been focused on AGVs, medical robots, welding robots and painting robots, as significant examples of the importance of path planning in robotics. In particular, the latter field of application has been analyzed in detail. The analysis has outlined the uttermost importance of path planning in the development of effective robotic operations, as path planning can be used as tool to face the technical challenges of modern industry.

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