Optimization-based path-planning framework considering process properties of industrial manufacturing processes

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***Abstract*— This paper presents a flexible robotic path-planning framework for complex industrial processes. The framework considers the process properties, including process tolerances and windows, constraints, and redundant degrees of freedom. By considering the process properties in an optimization-based approach, challenging path-planning problems can be solved which exceed the capabilities of state-of-the-art path planners. The effectiveness of the path planner is validated through two different scenarios: a drawing process and a spraying process. The results demonstrate the ability of the proposed framework to generate feasible trajectories for executing complex industrial processes.**

I. Introduction

The number of employed industrial robots is increasing rapidly [1], and there is a growing demand for flexible production systems that can handle product diversity [2], [3]. CAD-based offline path-planning approaches are commonly used to plan the motions of industrial robots in automated manufacturing processes. However, if the requirements exceed the capabilities of the robotic system or planning algorithm, laborious procedures such as adapting the manufacturing paths [4] or using a different robot may be necessary [5]. Incorporating the specific properties of the executed process into the path planning can significantly increase the flexibility of a given robot work cell.

The work [6] introduces a nomenclature on process properties, universal to numerous industrial processes with continuous manufacturing paths. The Cartesian degrees of freedom (DoF) of the tool needed to accomplish a manufacturing task are called *process DoF*. Most processes require all six DoF for the tool (e.g., cutting, sewing), while some only require five (e.g., drilling, polishing), with the remaining DoF referred to as *redundant process DoF*. Some processes allow for deviations from the manufacturing path. *Process windows* refer to allowed deviations that do not degrade process quality, and *process tolerances* refer to deviations that degrade process quality to a tolerable extent. *Process properties* include the process tolerances, process windows, constraints, and redundant process DoF and are used to specify a manufacturing process. For example, in a polishing process, the orientation may deviate slightly from the surface normal, but the contact point on the surface should follow the desired path exactly. The rotating disk represents a redundant process DoF.

Path-planning algorithms can be classified based on their underlying methodology, i.e., sampling-based [7] or optimization-based [8]. Additionally, pathwise inverse kinematics [9] can be used to compute trajectories for given continuous end-effector paths. Several path planning algorithms have been developed for specific manufacturing processes, incorporating only the relevant process properties for that particular application, such as welding [10], surface inspection [11], sanding [12], and chamfering [13].

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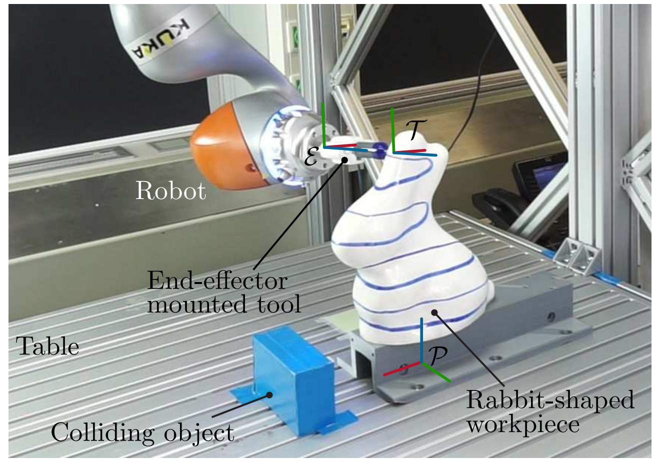

Fig. 1. Experimental setup for the drawing process after completing the process. The coordinate systems and robot joints are annotated.

This workshop contribution presents the recently published work [6], in which an optimization-based path-planning framework is proposed, which systematically incorporates the process properties as a general framework of cost terms and equality and inequality constraints. In addition, this path planner also incorporates a collision avoidance method and can plan through kinematic robot singularities. This increases the search space significantly and solves path-planning problems that state-of-the-art planners cannot solve. A video summarizing the algorithm and the experimental results is found at www.acin.tuwien.ac.at/4adf/.

II. Manufacturing process

1) Robot and tool: The forward kinematics of the robot with n DoF $\mathbf{q}^{\mathrm{T}} = [q_1 \cdots q_n]$ describes the pose of the end-effector frame $\mathcal{E}$ w.r.t. the robot base frame $\mathcal{B}$ and is given by the homogeneous transformation $\mathbf{H}_{\mathcal{B}}^{\mathcal{E}}(\mathbf{q})$. Note that the notation $(\cdot)_{\mathcal{A}}^{\mathcal{B}}$ refers to mathematical objects describing the geometric relation of the frame $\mathcal{B}$ w.r.t. $\mathcal{A}$, expressed in $\mathcal{A}$.

In the manufacturing process, the homogeneous transformation $\mathbf{H}_{\mathcal{P}}^{\mathcal{T}}(\mathbf{q})$ describes the motion of the tool center point (TCP) $\mathcal{T}$ w.r.t. the workpiece frame $\mathcal{P}$. Depending on the manufacturing process, $\mathbf{H}_{\mathcal{P}}^{\mathcal{T}}(\mathbf{q})$ is specified differently, whether the tool is mounted on the robot's end effector while the workpiece is stationary or vice versa.

2) Manufacturing path: A manufacturing path is given as a sequence of poses $\mathcal{H}_{\mathcal{P}}^{\mathcal{M}} = \{\mathbf{H}_{\mathcal{P},i}^{\mathcal{M}}, i = 1, \ldots, m\}$, where each pose $\mathbf{H}_{\mathcal{P},i}^{\mathcal{M}}, i = 1, \ldots, m$, describes the manufacturing frame $\mathcal{M}$ w.r.t. the workpiece frame $\mathcal{P}$, i.e., the desired tool pose during process execution.

3) Process DoF and process properties: The process windows and tolerance bands of the process DoF are specified by the minimum and maximum allowed displacements $\mathbf{d}_{\min}$ and $\mathbf{d}_{\max}$ and the minimum and maximum rotations in terms of roll-pitch-yaw angles $\phi_{\min}$ and $\phi_{\max}$, respectively, of the tool frame $\mathcal{T}$ w.r.t. the tool frame $\mathcal{T}$. Additionally, individual axes in the manufacturing frame $\mathcal{M}$ can be specified as redundant process DoF, e.g., the rotation axis of a drill or a polishing disk.

III. Optimization-based path planning

The optimization-based path planning is formulated as a series of optimization problems, which are solved using a set of starting configurations for the robot.

1) Starting configurations: First, the set $\mathcal{H}$ containing all feasible initial tool poses is derived from the first manufacturing frame $\mathbf{H}_{\mathcal{P},1}^{\mathcal{M}}$ by considering all process properties. Then, the discrete subset of all feasible joint-space configurations $\mathcal{Q}_f$ for the set of initial frames $\mathcal{H}$ is computed, wherein the redundant DoF of kinematically redundant robots are sampled. The number of initial joint configurations is reduced by filtering $\mathcal{Q}_f$ using a minimum-distance criterion, which yields the reduced solution set $\mathcal{Q}_g$ containing e_g solutions.

2) Optimization problem: Starting from each joint-space solution $\mathcal{Q}_g$, a series of optimization problems is solved sequentially. Each series is given by

$$\mathbf{q}_{u,i}^* = \underset{\mathbf{q}_{u,i} \in \mathbb{R}^n}{\arg\min} \; f(\mathbf{q}_{u,i}, \mathbf{H}_{\mathcal{P},i}^{\mathcal{M}}) \, , \quad i = 1, \ldots, m \tag{1a}$$

$$\text{s.t. } \mathbf{c}_{\text{eq}}(\mathbf{q}_{u,i}, \mathbf{H}_{\mathcal{P},i}^{\mathcal{M}}) = \mathbf{0} \tag{1b}$$

$$\mathbf{c}_{\text{ineq}}(\mathbf{q}_{u,i}, \mathbf{H}_{\mathcal{P},i}^{\mathcal{M}}) \leq \mathbf{0} \quad , \tag{1c}$$

where the initial guesses $\mathbf{q}_{u,i,0}$, $u = 1, \ldots, e_g$, are chosen from the set $\mathcal{Q}_g$ for $i = 1$. For $i > 1$, the solution from the previous optimization $\mathbf{q}_{u,i-1}^*$ is used. Based on (1), all feasible joint-space paths for all initial solutions $\mathcal{Q}_g$ are found.

With the proposed optimization-based path-planning approach, the objective function f and equality and inequality constraints $\mathbf{c}_{\text{eq}}$ and $\mathbf{c}_{\text{ineq}}$, respectively, are tailored to precisely describe the considered manufacturing process and its process properties. The objective function f is constructed as a sum of p cost terms f_j, $j = 1, \ldots, p$, which can consider position deviations, orientation deviations, collision avoidance using the algorithm *V-Clip* [14], and path continuity. Equality or inequality constraints can also be applied to individual deviations and joint limits. Process tolerances are implemented by combining cost terms and inequality constraints. The mathematical definitions and further details are given in [6].

3) Optimal joint-space path and trajectory generation: The optimal joint-space path $\mathcal{Q}^* = \{\mathbf{q}_1^*, \ldots, \mathbf{q}_m^*\}$ is determined by summing up the (partial) cost of each feasible joint-space path found in (1). As a final step, the joint-space path $\mathcal{Q}^*$ is time parametrized, which yields the piecewise trajectory $\mathbf{q}^*(t)$ with the sample points $(t_i, \mathbf{q}_i^*)$, $i = 1, \ldots, m$.

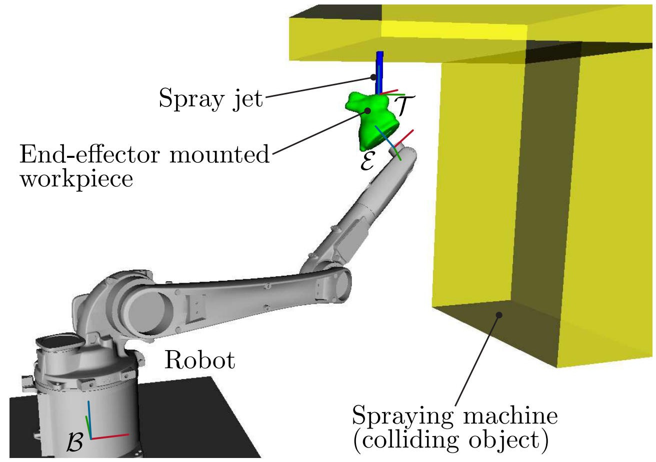

Fig. 2. Setup for the spraying process in simulation. The coordinate systems and robot joints are annotated.

IV. Experimental results

This section applies the proposed path-planning framework to two applications with distinct process properties. Only the weighting matrices of the objective function terms must be adapted and the proper constraints need to be enabled or disabled to represent the specific manufacturing process accurately. The path-planning framework successfully exploits the process properties in both applications to plan feasible robot trajectories.

1) Drawing process: In this process, the kinematically redundant industrial robot Kuka LBR iiwa 14 R820 with a marker mounted on the end effector has to draw a line on a 3D-printed rabbit as specified by the desired manufacturing path, see Fig. 1. The rectangular nib of the marker allows to draw thick and thin lines by rotating it around the surface normal vector. In the path-planning framework, the process is implemented by constraining the nib position while allowing tolerances in the orientation. The blue box, which prevents the robot from reaching several points of the manufacturing path without tolerances, is implemented as colliding object.

2) Spraying process: In the spraying process, the workpiece is mounted to the end effector of the industrial robot Kuka Cybertech KR8 R1620, which moves the workpiece below a rotationally symmetric spray nozzle along the manufacturing process, see Fig. 2. Hence, in the path-planning framework, the rotation around the spraying axis is considered a redundant DoF, while its alignment is constrained to the surface normal vector. The lateral position is constrained, while small tolerances are implemented for the distance between the spray nozzle and the surface.

V. Future work

Future works will be concerned with further improving the computation time for the path planning of long manufacturing paths with high resolution and multiple collision objects. Additionally, by incorporating the dynamic model of the manipulator into the path-planning framework, time-optimal or energy-efficient joint-space trajectories can be obtained.

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