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Non-nominal path planning for robust robotic assembly

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ABSTRACT

In manufacturing and assembly processes it is important, in terms of time and money, to verify the feasibility of the operations at the design stage and at early production planning. To achieve that, verification in a virtual environment is often performed by using methods such as path planning and simulation of dimensional variation. Lately, these areas have gained interest both in industry and academia, however, they are almost always treated as separate activities, leading to unnecessary tight tolerances and on-line adjustments.

To resolve this, we present a novel procedure based on the interaction between path planning techniques and variation simulation. This combined tool is able to compute robust assembly paths for industrial robots, *i.e.* paths less sensitive to the geometrical variation existing in the robot links, in its control system, and in the environment. This may lead to increased productivity and may limit error sources. The main idea to improve robustness is to enable robots to avoid motions in areas with high variation, preferring instead low variation zones. The method is able to deal with the different geometrical variation due to the different robot kinematic configurations. Computing variation might be a computationally expensive task or variation data might be unavailable in the entire state space, therefore three different ways to estimate variation are also proposed and compared. An industrial test case from the automotive industry is successfully studied and the results are presented.

1. Introduction

A common scenario when simulating manufacturing and assembly processes includes an engineer trying to simulate the process by manipulating objects in a digital mock-up software. In highly geometrical restricted assembly situations, this procedure is often sensible to errors and is time consuming. Furthermore, it is common that such manufacturing and assembly tasks are performed by robots, whose motions are difficult to plan and control by manual programming. If we also consider that, in reality, every physical object is subject to geometrical variation due to its manufacturing process, then it appears prohibitive for an engineer to verify the feasibility of the assembly procedure at an early stage. An automated verification is therefore helpful, since it can decrease the enormous costs that arise when realizing the infeasibility of an assembly plan late in the production phase, and the following need to re-design the process and/or the products.

Robots performing assembly operations are subject to variation as any other assembly system. Another variation source comes from robot *resolution*, mainly due to the precision of the computing system and to sensors and actuators sensitivity. Resolution affects also the *accuracy* of the robot, which is a measure of how close to the nominal value the robot can reach. The accuracy, then, influences the *repeatability*, which is the ability of a robot to perform the same task in the same manner, see [1].

1.1. Motivation

One way to substantially improve positional accuracy is by on-line teaching the robot the poses it will assume during its assigned operations: in this way the robot controller stores its internal state and the data on how to perform the same task in the future, see [2] for advances in on-line programming environments. Anyway, programming robots on-line in order to perform tens or hundreds of tasks, with their respective paths and via-points, can be prohibitive.

Another way to achieve more accurate programs is by robot calibration: during this operation the mechanical parameters of the robot model are identified, see [1,3], e.g. by measuring the differences between the estimated position of the Tool Center Point (TCP) and the actual one. Anyway, the results may vary depending on which area of the workspace the calibration is done, on the robot's load, as well as on speed and acceleration of the motion. Moreover, it is difficult to compensate for uncertainties in the robot's degrees

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of freedom (dofs) due to sensors and actuators resolution. Nonetheless, even if the TCP behaves in the virtual world exactly as in the real world, the robot might in reality collide with the environment, whereas its nominal model does not: this might be caused by geometrical variation introduced during the manufacturing and the assembly of the robot links.

However, in many cases, even after the identification of the mechanical parameters, it is not possible to update the models in the simulation software. This can happen since software may be provided by third part actors, because the off-line programming (OLP) is done only once, before calibration, or because the motions are programmed for a broad class of robots with similar geometric characteristics. All these considerations motivate the fact that OLP software has to take into account geometric variation both in the robot parts and in the environment. Modeling and dealing with these aspects helps in producing robust and more reliable solutions, not so sensitive to the uncertainties described above. In this paper we have such a goal and propose a method for planning of robot paths performing assembly tasks in presence of variation.

1.2. Contribution and related work

Our main contribution is to adapt and extend the ideas in [4,5], in order to handle non-nominal path planning for robot in presence of geometrical variation. In fact, [4] describes how to obtain geometrical variation of the robot TCP for a particular configuration. However, in this article, we introduce and compare different ways to estimate variation of robot configurations. The reason for that is that it would be too time consuming to compute variation for all configurations needed for the path planning algorithm. Furthermore, [5] is extended from rigid bodies to articulated mechanisms as robots. Nonetheless, the algorithm is refined and improved by tuning the distance function for practical cases, and the variation is handled in the smoothing step.

The main idea is, firstly, to generate a robot path by state-of-the-art automatic robot path planning, then the path is post-processed by a smoothing algorithm trying to minimize the probability of collision. Variation analysis is performed in order to modify the distance measure needed to smooth the initial path.

Two main research areas can be identified related to this work:

- variation analysis and robust design;
- path planning in presence of uncertainties.

Many articles are dealing with geometrical variation, see [6], which have also resulted in software tools, [7]. In this work the variation analysis is done according to [4] and is used to compute variation for the positions of the each robot link along a robot path. For an overview of modeling methods for positioning rigid bodies by locating schemes, see Section 2.

The research area of path planning under uncertainties is wide, dealing with uncertainties in the models, in the sensors, and in static and dynamic environments, see [8,9] for an overview. In our application, the most relevant uncertainties come from geometrical variation in the environment and in the robot. In [10] the uncertainty in the robot is translated into a probability ellipsoid which is geometrically added to the moving object. The disadvantage with this method is that a required likelihood often leads to infeasible paths. In our work, instead, we do not fix a priori the wished probability of a path being collision-free and we do not explicitly incorporate the probability ellipsoids in the geometrical models: this allows skipping computationally expensive steps. In [11] the path planning algorithm tries to minimize an objective function trading between the path length and the probability of collision, by computing lower and upper bounds for the collision probability and refining the bounds during the search, when needed. The problem is the computational complexity of the approach for complex 3D models. At the same way, the approaches in [12,13] show only results for simple landmark obstacles or for 2D models.

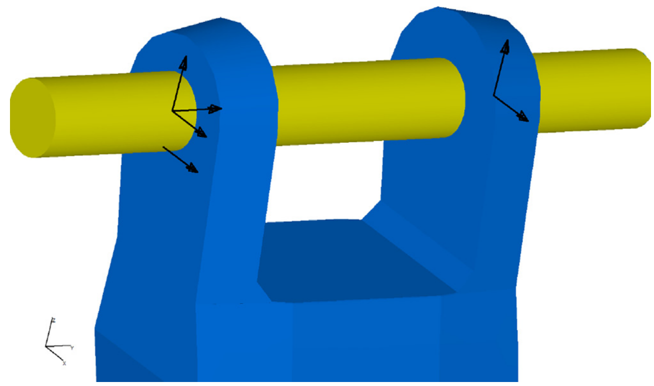

Fig. 1. Revolute joint with its locating scheme.

Our work, on the other hand, based on [5], overcomes this limit by providing a general method to handle uncertainties using bounding volumes hierarchies. It also decouples the collision query phase from the sampling based search, by allowing the reuse of existing search methods. Furthermore, by integrating variation analysis with path planning, we can perform variation analysis on the robot configurations we are interested in (along the nominal path), and not on the entire robot configuration space: this allows flexibility in obtaining good variation information without prohibitive computational effort.

1.3. Outline

The outline of the article is the following: in Section 2 the locating scheme and variation simulation are briefly described; in Section 3 an introduction to robot path planning is presented; Section 4 covers proximity queries in presence of variation in the models, how robot path planning can handle uncertainties and how to estimate variation when explicit data are not available. Eventually, Section 5 illustrates an industrial case where the method presented is successfully applied.

2. Locating scheme and variation simulation

In order to determine the position and orientation of a rigid body six dofs must be locked. Different approaches are used nowadays, see [14,15], for examples. Here, we consider the locating method that consists in defining six locating points, or locators, defining a *locating scheme* and then forcing the object to be in contact with them, [6]. Given such a deterministic locating scheme the position of the object is completely identified. This model can be used to simulate the fixturing process for workpieces and for assemblies, as a robot for example. An industrial robot usually consists of a number of links joined with actuated joints. By considering the links as rigid bodies, it is possible to build an assembly model of the robot, see [4]. Depending on the geometry of the joints this can be done in a number of ways. Here we consider the most common type of joint: the *revolute joint*.

One type of revolute joint consists of an axis rotating relative to two holes in a yoke, see Fig. 1. The position of the part connected to the axis is mainly determined by the contacts between the axis and the holes. In this case the locating scheme can be defined in the following way: