Title:
An Overview of an Enhanced Multi-Systems Robotized Digitizing

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Introduction:

Nowadays, robots are widely used in industry for repetitive tasks with low pose accuracy as handling, painting or welding. Usually, industrial robots have poor pose performances that limit their use for high precision task especially for measurement applications. However, they offer a great flexibility of movement with 6 degrees of freedom (DoFs) and a high speed of execution. Those characteristics stay very attractive and could allow the 3D digitizing of large manufacturing parts taking advantage of the continue reorientation offered by robots while facilitating its integration in production lines. But this could not be done without increasing the pose accuracy of the robot, as defined in ISO 9283 [12].

In this context this paper deals with the introduction of a 3D digitizing cell using a robot as displacement system and addresses an approach to use it for parts digitizing with given quality required by the applications. The strategy introduced paid also attention to other optimization criteria such as digitizing speed. The result will be a part digitized with a given quality and an optimized speed. The technology chosen for this cell is a Laser Triangulation Sensor (LTS) for scanning and a 6-axis robot to support the digitizing. The digitizing result highly depends on the LTS and on the robot performances, which are both studied in this paper. LTS calibration is well known yet there is a lack of standardization about measuring LTS performances, and we need adapted methods [7]. On the other hand, robot performances are also drawn from experiments or from a model. Yet models used for industrial robots are commonly simple and take into account 1 or 2 more parameters than the classic DH modeling. So, we investigated an original and accurate elastic and geometric model for the robot and propose a convenient method for the identification of its parameters. We can also show that robot performances are heterogeneous in its workspace [8]. So, depending on these performances, the choice of a zone in the robot workspace to realize the digitizing is crucial for quality or speed. Based on robot performances cartography and on LTS performances, a path planning algorithm is introduced. The investigation on path planning is essential in order to answer the quality imposed by digitizing application. The optimum path planning requires the use of the robot and the LTS in their best configuration regarding the quality/speed. Completed with the robot model, the approach allows to generate the best path planning to optimize quality, speed but also other criteria (not investigated here) such as energy consumption and so on.

In order to respect the quality of the resulting digitizing, an external system can control the path followed by the robot. Many applications only rely on the robot model or only use an external measurement system to correct the path online. Using both of them brings a redundancy that gives a more robust result.

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Global approach for the robotized digitizing:

The 6 DoFs of the robot allow a more complex path planning which helps to respect digitizing requirements and to optimize other criteria such as speed, quality or energy consumption. For this purpose, we discuss the exploitation of the robot performances but also the integration of LTS assessment into the path planning algorithm to calculate the best path depending on robot and sensor performances

Multi-sensor digitizing cell

Many papers deal with the integration of robots for a specific application, for instance machining with robots is a big concern in literature [1]. Brosed [3] and other authors use robots in a digitizing process but they use it to hold and position parts with specific orientation. The robot is not integrated to the path generation and full robot capabilities are not used.

Path planning is inherent in the use of robots and allows taking advantage of the 6 DoFs available to improve the robot posing [11]. Path planning should be based on robot performances thanks to robot performance indexes [8]. But as related by Zha [11], most of the performance indexes are not taken into account for path generation. Otherwise, the robot's model used plays also a major role on the robot posing and therefore on the quality of the cloud of points. Indeed, the definitions of performance indexes are mostly related to the robot model. This is why great attention must be paid on the selection and/or the definition of the model.

In this context we use a digitizing cell (Fig. 1.) which combines two contactless sensors: one for the part digitizing and one external for the robot trajectory control.

This cell allows introducing a global approach to generate a cloud of points respecting a given quality for a given application while taking advantage of the robot's capabilities. The approach can be divided in 2 parts: the path planning related to robot performances; the deviation control and post-processing for the quality improvement.

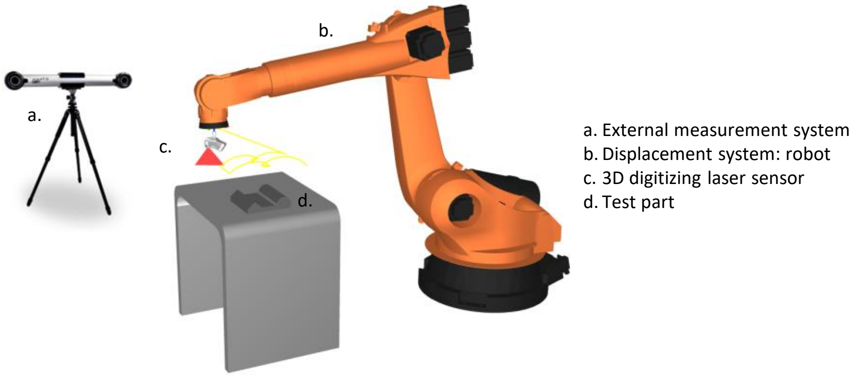

Fig.1 Multi-sensors digitizing cell.

Path planning for digitizing quality improvement

The path planning algorithm leads to the selection of an optimal trajectory (for quality, speed or energy), which should be implemented on the robot for a given quality requirement of the resulting cloud of points. As described on Fig. 2., the digitizing path planning starts with the study of specifications and the requirements of the application in terms of speed and quality. A CAD part is also used to know the part geometry. Thanks to the sensor performances knowledge, the requirements are translated defining the local path specification, particularly digitizing distance and angle between the sensor and the part. Then we look for an area in the robot workspace to respect local path specifications: a set of admissible area is identified. Among the admissible areas, the optimized path in terms of speed and robot posing quality (or any added optimization criterion) is carried out. In order to perform this approach, it is necessary to have a perfect knowledge of the LTS characteristics used. The sensor used is a KREON KZ25 and its performances are evaluated with the application of an

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assessment protocol: QualiPSO [18]. Robot performances and path generation in Fig. 2. are based on an accurate model of the robot introduced in the next section.

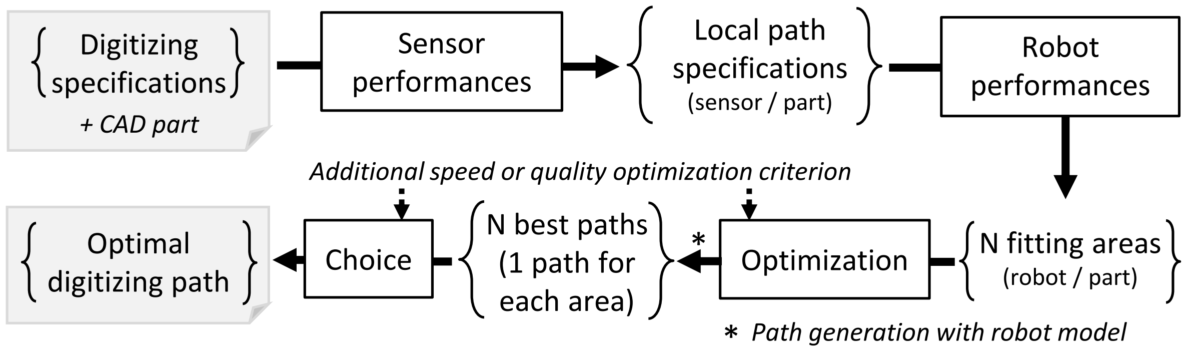

Fig. 2: Path generation approach for digitizing.

Robot modeling:

The path planning strategy is used to respect and optimize the quality of digitized points and the speed of the digitizing process regarding the requirements on the digitizing. But the success of this strategy is strongly linked to the accuracy of the robot model used. During the execution of the generated path planning, the robot model defines the relation between the Cartesian space and the joint space. Indeed, the path is generated in Cartesian space but the robot motion is defined in the joint space. So, a poor robot model would result in an offset of the desired optimized path and would affect the quality of the digitizing points.

Moreover, the next section shows the dependence of many robot performances on the robot modeling. So, in our approach, the model is the main base to calculate robot performances indexes and to improve the quality of digitized points. The classical model used in the CNC (Computer Numerical Control) of our robot to generate path doesn't take into account most of robot defaults. To fill this gap, the model has to be as detailed as possible to manage real robot behavior. In this way, the model should take into account geometric defaults from manufacturing limits or errors, and non-geometric defaults like deformations or backlashes.

Model Choice

Among numerous geometric models proposed in literature, the Denavit-Hartenberg (DH) model is the best-known basis. And to date, the most used model is the DH modified model as it is more convenient [6]. It is usually completed with the Hayati parameter to handle consecutive parallel axes. But we focus more on elastic models, as we need both geometric and non-geometric defaults. Most of elastic models are based on the DH model and vary with the number of non-geometric defaults considered [4]. In order to define a really complete model, three techniques are more developed: the FEA model (Finite Elements Analysis); the MSA model (Matrix structural Analysis) [5]; the VJM model (Virtual Joint Model) [9].

We need a model including all significant defaults for our application, so the best choice is an adaptable model that can be completed with any needed parameter. We choose the VJM model, initially made for deformations only, as the basis of our model. We modified its 6 DoFs virtual joints into a vector for translations and a vector for rotations. The model is then more flexible and can take into account deformations, backlashes and could be open for the integration of other phenomena.

The VJM model has a DH based geometric model and we use its additional virtual joints to represent non-geometric defaults of robot joints and links. The links are modeled with the beam theory from the MSA model [5]. It represents their deformations under external load and robot own mass with 6 inner parameters (5 springs and one mass).

Robot joint modeling is commonly less detailed: only an angular error around the axis is classically included. To get a more complete model, we use the standard ISO 230-1, in a polar frame under special conditions to get 4 error terms [13]: dr (radial error motion); dz (axial error motion); δr (tilt error motion); δz (angular positioning error motion). In each of them we include deformation and backlash to get a total of 8 parameters for the robot joint model.

Identification of model's parameters

To identify model parameters, we choose a contactless method with an external measurement system (Fig.1) for more convenience as digitizing can be done on production lines. We also want to represent robot behavior well in its entire workspace, and not only in few spots used by most of calibration techniques. In this way the circle point analysis (CPA) method [10] is applied. CPA identification is usually used for geometric calibration and we adapted it to get also elastic parameters with the Levenberg Marquardt algorithm.

A first identification of geometric parameters is done assuming rigid links and perfect joints. These results are then used as inputs to calculate iteratively elastic parameters and geometric parameters, using each previous result. The calculation goes on until parameters accuracy reaches a given stop criterion. Once parameters are known, the model is used for path planning and performance indexes.

Exploitation of robot performances:

The digitizing trajectory generated by the path planning algorithm will result in a set of path points describing the sequential effector positions and orientations. The goal of path planning is to identify the optimal positions and orientations of the robot effector in terms of quality, speed or energy saving. In this way, we use index models, based on the identified robot model to calculate robot performances for any configuration of the effector. Moreover, it is interesting to see how the quality of indexes computations depend on the quality of the model previously introduced: the robot model has to be as close as possible to the real robot behavior.

The robot performance assessment applied allows us to generate cartography required for path optimization that describes robot speed to optimize the digitizing time. They also need to describe the fidelity of the path followed by the robot, or the quality of robot posing in order to ensure a path quality and so a digitizing quality. Among existing indexes [8], we look for those related to the robot speed, posing quality, but also other useful criteria that can influence indirectly speed or quality. Then during the path optimization process, all those indexes are taken into account with different weights depending on their importance for the calculation.

Among the existing indexes we choose the manipulability. This index is related to the robot speed and posing quality so it is crucial for the path planning. Then we control the matrix conditioning and limit error propagation in calculation thanks to the condition number. We also use a convenient index to control articulation limits and to smooth the path: the articulation availability. Finally, we include the uncertainty of robot posing with the robot repeatability. For this last index we developed our own model based on Brethé's method [2].

Operation tracking with external measurement system:

In order to have a more robust quality on the digitizing points, we use an external measurement system to follow the execution of the generated path by the robot. Moreover, the quality of the parameters identified for the robot model depends on that external system which is also used for calibration. So, this section is dedicated to a study and a qualification of this system.

The external measurement system of the cell (Fig.1) is a stereovision system: the CTrack. Although it lengthens the cycle-time with additional calculations [5], the external measurement system (Fig.1) is firstly used to follow the robot trajectory and to control deviation. Even if the previous calibration of the robot model is accurate, the redundant use of an external system to correct the path allows ensuring the quality of digitizing results.

The external system is also used to increase the quality of the cloud of point registration, if robot joint coordinates are known. The robot model and angles given by robot sensors allow knowing the robot configuration during digitizing, but the external system can increase or confirm the validity of this configuration.

This external measurement system also helps to identify robot model's parameters during calibration (with CPA method). A qualification of this system is thus important as it is used for many purposes in this digitizing cell. An assessment protocol has been achieved on this external system checking the adequacy of its performances with requirements of the different uses. This protocol includes the measurement of CTrack performances and the computation of the CTrack error propagation in the different calculations.

Conclusions:

The capability to digitize with a robot in an industrial context for a given quality is a request that would allow saving time and resources. To date digitizing at a giving quality with robots is not developed and robot advantages are not fully exploited. In contrast to previous work, the approach introduced in this paper allows to take advantage of full performances of robot and the digitizing sensor to get an optimized quality result. In this way an optimized path is identified among an admissible set previously identified. The path planning process is articulated around two main criteria: the final quality of the resulting cloud of points and the digitizing time. In order to achieve a level of quality compatible with demanding applications, a complete and detailed robot model has been defined. The system is completed by an external measurement device used for the path deviation control and the continued improvement of the cloud of points.

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