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An overview of an enhanced multi-systems robotized digitizing

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ABSTRACT

Robots were commonly used for repetitive tasks, but to date they can handle more demanding processes like digitizing. Using a robot gives many advantages even though they still have a lack of accuracy when following a path. This paper focuses on an optimization strategy to get the best quality or/and speed for 3D digitization supported by a robot. In this way, a path planning algorithm is introduced based on the exploitation of robot and digitizing sensor performances. In order to define the robot calibration and its performances assessment, an original adapted model is investigated. An optimization step is integrated to the path planning algorithm in order to identify the best path (regarding the digitizing quality and time) among a set of admissible one. Finally the implementation of the selected path planning is carried out and the robot is monitored by an external measurement system in charge to correct this path to ensure the quality of digitizing.

KEYWORDS

3D digitizing; multi-systems; path planning; quality optimization

1. 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), a better accessibility than CMMs and a high speed of execution. Those characteristics stay very attractive and allow the 3D digitizing of large manufacturing parts as well as little complex 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, and confirmed by industrial needs [23],[30].

In this context this paper deals with the introduction of a 3D digitizing cell using a large 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 criterion such as digitizing speed. The result will be a part digitized with a given quality and an optimized speed. The main application target is the control of manufactured parts so the CAD part is available and the strategy can use it. Application is control from CAD part of a manufactured part but could also reverse engineering.

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 [24] yet there is a lack of standardization about measuring LTS performances, and we need adapted methods [18]. 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 [6],[21]. 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 [20]. 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 which means using the robot and the LTS in their best configuration regarding the quality/speed required. Starting with the CAD part and with the LTS and robot information, the approach allows to generate the optimal path with an optimized quality, speed but also other criterion (not investigated here) such as energy consumption

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for instance. The CAD part is supposed available as the main application targeted is manufactured parts controlling on production lines. Moreover the digitizing cell could also be used for reverse engineering.

In order to respect the quality of the resulting digitizing, an external system controls the path followed by the robot. LTS positioning with stereovision systems already exists in commercial solutions proposed for example by Kreon or Creaform. But they don't look at path generation and are independent from the robot used or the part to digitize. Moreover like many applications, they only rely on the use of an external measurement system to correct the path online and don't look at the robot model. Using both of them brings us a redundancy that gives a more robust result with a mastered uncertainty.

After the introduction of the digitizing system, the global approach and the path planning are detailed. In the third section the robot's model definition is discussed and in the fourth one we present different performance indexes that we choose in order to exploit the robot capabilities. In the fifth section the external measurement system used to control the robot deviation is introduced as well as the LTS calibration, before ending by a conclusion and future works.

2. 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 optimal path depending on robot and sensor performances (regarding quality or speed).

2.1. 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],[9],[21]. Brosed [4] and other authors [24] 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 [15],[16],[19],[28]. Path planning should be based on robot performances thanks to robot performance indexes [20]. But as related by Zha [28], most of the performance indexes are not taken into account for path generation. Otherwise, the robot's model used plays also a major role for 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 [8],[11].

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 for the quality improvement and post-processing.

2.2. Path planning approach

The path planning algorithm leads to the selection of the best trajectory, which should be implemented on the robot for a given quality requirement of the resulting

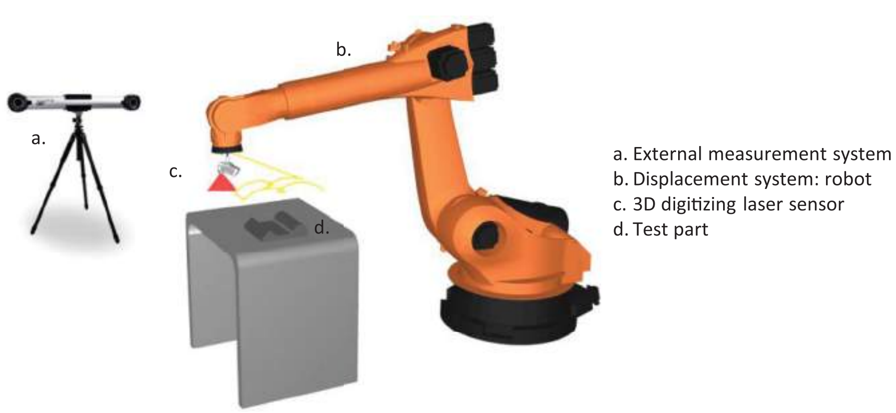

Figure 1. Multi-Sensors Digitizing Cell.

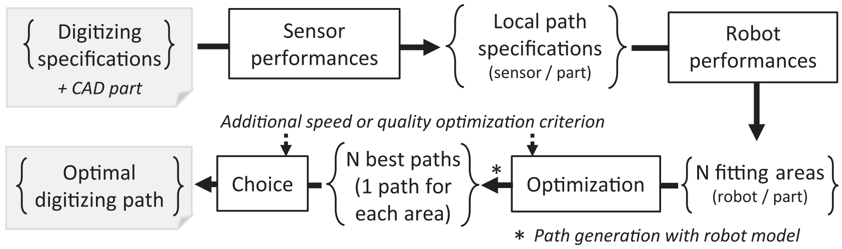

Figure 2. Path Generation Approach for Digitizing.

cloud of points. The path is a set of path points describing a position and an orientation of the robot effector. When the robot CNC will read the path, the robot model used will allow to convert points from the Cartesian space to the joint coordinate space which is actually used to move the robot. Then during the execution more points will be created by linear interpolation between the existing points in order to smooth the trajectory.

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, optimized paths are generated in terms of speed and robot posing quality (or any added optimization criterion). At this step, an additional optimization criterion or a threshold in terms of speed or specified uncertainty can be imposed by the user to set the path. In this way the final optimal path will respect digitizing specifications and will be optimized regarding criteria chosen by user.

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 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.

3. 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 wanted optimized path and would affect the quality of the digitizing points.

Moreover the fourth 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 computer numerical control 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, we introduce a model taking into account geometric defaults from manufacturing limits or errors, and non-geometric defaults like deformations or backlashes. We also developed an original method to determine model parameters efficiently and conveniently.

3.1. Model choice

Among numerous geometric models proposed in literature, the Denavit-Hartenberg (DH) model is the best-known basis [6]. And to date, the most used model is the DH modified model as it is more convenient [13]. It is usually completed with the Hayati parameter to handle consecutive parallel axes [10]. 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 [7],[26],[27]. In order to define a really complete model, three techniques are more developed:

- The FEA model (Finite Elements Analysis) uses finite elements and flexibility parameters to compute robot deformations [2].
- The MSA model (Matrix structural Analysis) uses Euler-Bernoulli beam theory to compute robot deformations [12].

- The VJM model (Virtual Joint Model) uses virtual springs with 6 DoFs to handle displacements between joints and links due to deformations [22].

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 the 6 DoFs virtual springs 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. Moreover the VJM method allows calculating the robot position quickly.

The VJM model has a DH based geometric model and adds virtual joints between geometric parts, as explained in Fig. 3 it is possible to separate models. The modified VJM model handles all non-geometric phenomena into vectors of its virtual joints. It represents defaults of joints and links. Models of joints and links are then required.

The links are modeled with the beam theory from the MSA model [12]. It represents their deformation under external load and robot own mass with 6 inner parameters (5 springs and one mass).

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 [31]:

- *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 joint model.

Although this model is general, we pay attention to special issues. For instance, in the robot geometry, the 3rd link, the 4th axis and the 4th link are aligned, which means that any configuration of the robot keep the 3rd and the 4th link aligned. So their length cannot be separated and must be identified together. Moreover the DH modeling cannot take into account the 3rd and the 4th length separately, a unique parameter is the sum of these length. Another issue is the nonconformity of some links of the robot with the beam theory. They are then modeled with the FEA model, or considered as non-deformable if measures show that they are too rigid.

3.2. Identification of model's parameters

To identify model parameters, we developed 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 [24]. In this way we based our method on the circle point analysis (CPA) technique [25].

For this method, robot axes are moved one by one in the field of view of the external measurement system. This system follows a point placed on the robot effector which will draw an arc. The CPA identifies axes location from arcs of points, then we calculate robot parameters between axes. The measurement system measures an axis

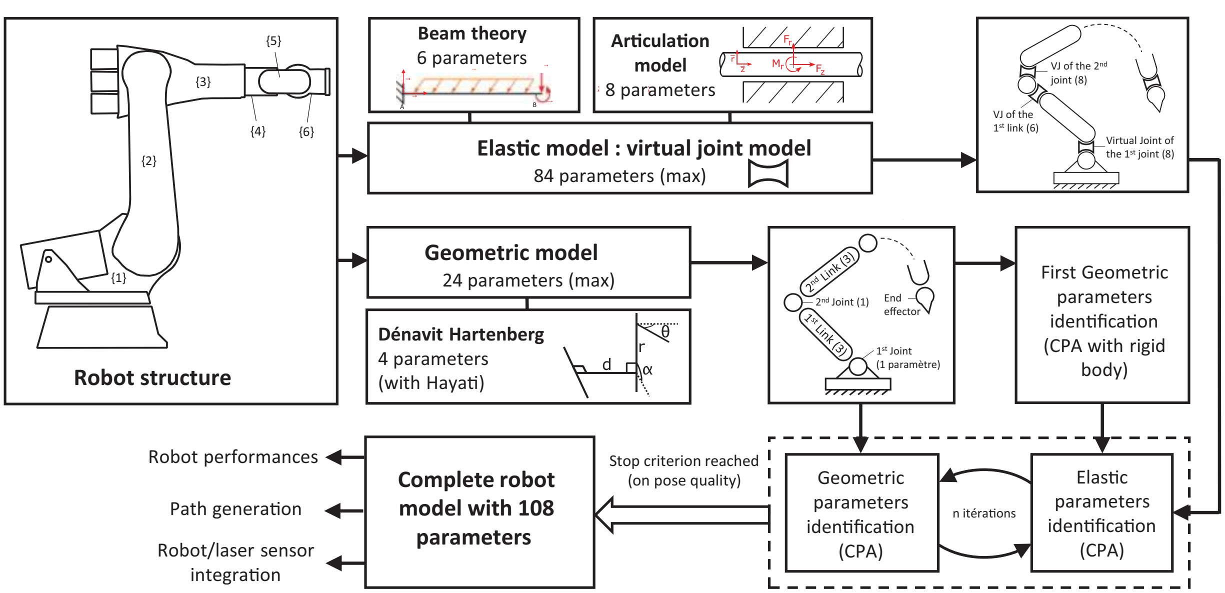

Figure 3. Calibration strategy for a complete model of the robot, based on the modified VJM model.

from an arc of points as long and as complete as possible. This method gives good axes positions and leads to a good identification of parameters. The longer the arcs are, the more representative of robot workspace the parameters will be. We don't look here for the minimization of position errors in few points, but for the direct estimation of robot parameters.

CPA identification is usually used for geometric calibration and we adapted it to get also elastic parameters. Experiments to get the axes arc are done with a variation of the efforts on the robot effector.

Then the calibration with the CPA method follows the strategy of Fig. 3, where a first geometric identification is done assuming a rigid body. These results are then used as inputs to calculate iteratively elastic parameters and geometric parameters, using each previous results. The calculation goes on until parameters accuracy reaches a given stop criterion. The more complex estimation of elastic parameters from measures is done with the robot elastic model and the Levenberg Marquardt algorithm to get the best suited parameters. Once parameters are known, the model is used for path planning and performance indexes. Current experiments give hopeful results on the parameters identification.

4. Exploitation of robot performances

The knowledge of robot performances allows to select the best robot positions and orientations for the digitizing regarding the specifications and additional criteria chosen by the user. As mentioned in previous section, the digitizing trajectory is then a set of path points (end-effector position and orientation) in the robot working space. Indeed various configurations of the robot could be used for a same position and orientation of the robot end-effector. That's why the assessment of the robot and the knowledge of its performances play a major role for the definition of the path planning. It helps determining the optimal path points but also the robot configuration for each point of the path giving the best digitizing quality or speed (or other chosen criterion). Of course the path planning strategy takes care of having a continuous and smooth path. In this way, we use index models, based on the identified robot model to calculate robot performances (in terms of quality, speed or energy saving) for any configuration and to get performance cartographies. Moreover, it is interesting to see how the quality of indexes computations are depending 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 [20], 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.

4.1. Manipulability index for speed and quality optimization

The manipulability is an index created by Yoshikawa and related to robot speed or posing quality [29]. It defines the robot potential movement for a configuration that is to say the robot capability to generate speed with his 6 axes on a given point of the workspace. The calculation of the manipulability index w on Eqn. (4.1) is based on the singular values of J the jacobian matrix of the robot model. Each axis contributes to the speed capacity as there is one singular value σ_i per axis i(i = 1,..,6).

$$w = |\det(J)| = \sigma_1.\sigma_2.\sigma_3.\sigma_4.\sigma_5.\sigma_6 \qquad (4.1)$$

This index can be used in a different way. When the robot cannot generate much speed on a configuration, an important movement of its axes creates a little movement of its effector. It means that his accuracy is much higher. So the manipulability index represents the robot speed capacity and the manipulability inverse renders the posing quality of the robot. That index can be used to determine either robot speed or posing quality.

Because of the jacobian matrix, the calculation of this index is based on the robot model. It means that a good model and a good calibration are necessary to get cartography closer to the real robot behavior. And we can see again the importance of robot modeling on the digitizing optimization and quality. In Fig. 4(a) we generated a cartography of the manipulability index calculated with the identified robot model, for an orientation of the effector. As the manipulability value highly depends on the number of robot axes, we use it to compare areas but we don't use the value itself.

4.2. Path generation quality with the condition number

The condition number is an index firstly used by Khan and Angeles, it defines matrix conditioning and limits error propagation [14]. The condition number uses the jacobian matrix of the robot model as on Eqn. (4.2), so

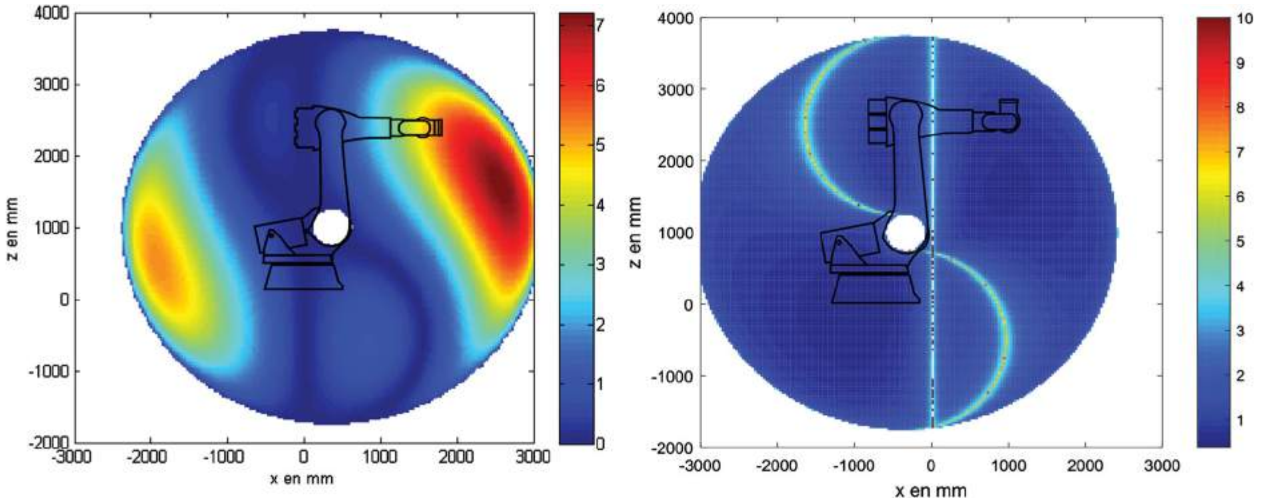

Figure 4. (a) robot manipulability for a given orientation of the effector. That cartography gives the best areas to generate movement. (b) The condition number through robot working area.

the model calibration also impacts that index.

$$K(J) = \frac{1}{6}\sqrt{tr(J.J^T).tr((J.J^T)^{-1})} = \frac{\sigma_{\max}}{\sigma_{\min}} \tag{4.2}$$

Many uses of this index exist, for accuracy, dexterity or error propagation. For example it gives velocities disparities between articulations. A low index shows a good repartition and a high index shows that an axis is reaching its speed limit. For a given orientation, Fig. 4(b) shows the condition number cartography we generated, where the areas to avoid are easily spotted because of high gradients. Like for Fig. 4(a)., the color depth of the condition number cartography mainly helps comparing areas and selecting them, but numerical values are unused.

4.3. Maximizing availability to smooth path

The articulation availability is a convenient index to smooth path, it allows controlling the position of articulations toward joint limits. It was firstly used by Liegeois to stay away from joint limits and to keep an amount of available movement [17], which helps having a smooth path. Yet it can't be used alone because it doesn't handle singular position problems. It is then combined with others indexes able to check singular positions like the manipulability index or the condition number.

This index is simply calculated from each joints limits as on Eqn. (4.3). Eqn. (4.4) shows the result which is a mean of each axes position toward their limits. An availability index tending to 1 means that axes are close to their limits, and a 0 value index means all axes have their maximum availability.

$$\Delta q_i = \left| q_i - \frac{q_{i\,\max} + q_{i\,\min}}{2} \right| \tag{4.3}$$

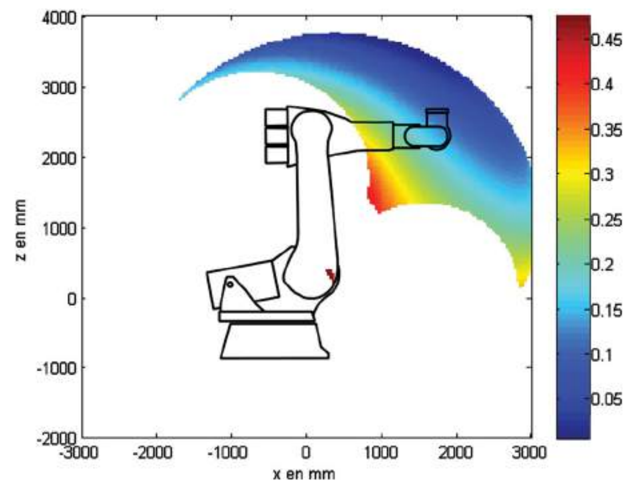

Figure 5. Articulation availability for a given orientation.

$$D = \frac{1}{n}\sum_{1}^{n}\left(\frac{\Delta q_i}{\Delta q_{i\,\max}}\right)^2 \tag{4.4}$$

That index helps to stay away from joint limits in order to smooth path, and, of course, it gives in its cartography the robot reachability like on Fig. 5. This helps to quickly select/eliminate impossible paths in robot workspace. So articulation availability cartography is combined with other performance cartography to obtain performances truly reachable.

4.4. Control of robot repeatability in its workspace

Repeatability is initially a performance value of the robot capability to repeat an action, for example to return exactly on a same point. It represents the uncertainty of the robot when trying to reach a configuration, that is to say the unpredictable part of robot posing. This index is expressed by the standard and used in industry as a single value giving the average robot repeatability, so this value doesn't depend on its configuration. Yet repeatability highly depends on robot configuration, so for more accuracy we developed a repeatability model giving the robot repeatability in a given configuration. This model is based on Brethe's work who built the robot repeatability from axis repeatability values [3]. Our model calculates axis repeatability value from the axis force, acceleration and speed. This model is employed for each axis and used to find the final robot repeatability for a given configuration with Brethe's method. As this index is based on its own model, an identification step was needed to get model parameters. A series of experiments gave each axis behavior depending on forces, speed or acceleration.

A cartography of that index allows to handle uncertainties and to select most reliable areas for the robot to follow a path.

5. Multi-sensor use for the robotized digitizing: qualification, integration and validation

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.

5.1. External measurement system

The digitizing cell is made of a 6 DoFs robot as a displacement system (support) and a LTS to digitize parts. But another important component of the cell must be described: the external measurement system. A Ctrack which is a stereovision system is chosen to get external measures for many contexts and purposes.

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 to ensure the quality of digitizing results. The deviation control is done in three steps: identification of the deviation of executed path from the nominal path; computation of the correction; generation of the new enhanced path. The computation time must be compatible with the cycle-time for a continued improvement of the digitizing.

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. In some other cases, the joint coordinates cannot be read from the robot sensors, and the external measurement system becomes essential for the computation of digitized points coordinates.

Calculation of digitizing points coordinates are generally done on line during the digitizing process. So the robot configuration, obtained from the joint coordinates and the external system measures, must be quickly given to the LTS. If this configuration takes too long to be calculated and transferred, its estimation should be simplified. Another solution consists in post-processing the LTS calculation in a point reconstruction step.

This external measurement system also helps to identify robot model's parameters during calibration. It is used in the CPA method described in the robot parameters identification section. It means that a qualification of this system is important because 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 is in two steps: firstly the measure of its own performances, secondly the calculation of the propagation of errors from the Ctrack performances for the concerned uses.

5.2. Integration of the LTS and validation

Even though we give robot configuration to the LTS, it also requires LTS parameters to get a cloud of points. Those parameters are known as extrinsic and intrinsic parameters. Intrinsic parameters describe the geometry of the laser sensor, it gives the relation between the 3D coordinates of a point seen by the sensor and the 2D vision of this point in the sensor CCD matrix. It takes into account the laser plane position toward the sensor frame, the optic characteristics of the camera and the resolution of the CCD matrix. The intrinsic parameters only describe the LTS inner properties, so they can be determined separately.

The extrinsic parameters are the parameters used in the equations linking the laser sensor and the support system (the robot here). The goal is to determine the configuration of the sensor in the robot base frame. Those parameters and the direct access to the robot configuration are really the main goal of LTS integration with a robot. To get extrinsic parameters, calibration gage placed in the robot workspace is generally used [24]. Its position is known in the robot base frame, the LTS needs then to digitize this object to get the extrinsic parameters.

The integration of the LTS can be done by attaching the sensor to the robot used as a support [24]. But the inverse can also be done: the LTS can be static and the robot can hold the part to digitize [4].

Lastly, a validation protocol must be conducted in order to check the validity of the whole digitizing process. A benchmark part was designed to test the 6 DoFs digitizing performances in terms of quality and speed. Both static and mobile LTS case will be checked to know:

- The quality when focusing on this piece with the path optimization
- The speed amount when focusing on this piece with the path optimization
- The capability of the system to reach the digitizing quality predicted during path generation

6. Conclusion

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 with robots is few developed, robots 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 based on the CAD part 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. In future work the digitizing cell will be tested with a large fuselage panel and with a part made by additive manufacturing to illustrate the contribution of robot accessibility both for large or complex parts.

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