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A digital solution for slender workpiece turning: the DRITTO project

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Abstract. Turning slender components is a critical task since workpiece flexibility entails relevant deformations during the process, leading to potential loss of accuracy, lower machining efficiency and higher manufacturing costs. The DRITTO project aims at developing an easy-to-use digital solution to support manufacturing of flexible axisymmetric components. The proposed support system, starting from the not-optimized toolpath, stock geometry and tool parameters, it will compute the optimized toolpath by integrating three different modules: a) workpiece FE modelling, b) turning process modelling, c) toolpath optimization. The project is ongoing, but, at the current stage, preliminary validation of the proposed solution has been carried out. DRITTO is funded as an experiment of DIH-World Horizon2020 project, and the consortium is composed by the machining services SME Meccanica Ceccarelli & Rossi and the University of Florence as part of the Digital Innovation Hub ARTES4.0.

Introduction

Manufacturing slender axisymmetric components is still a challenging task even with modern machining processes [1]. The turning process represents the main technology for the realization of such components because of its versatility and the high-quality standards achievable (i.e., surface roughness and geometrical/dimensional accuracy). However, demanding requirements in terms of quality usually conflict with the achievable productivity rates. Therefore, defining a proper machining cycle represents a crucial task in attaining the suitable trade-off between those two aspects. While surface roughness mainly depends on cutting parameters (i.e., feed rate) and tool geometry, the geometrical errors are influenced by the workpiece compliance: the deflection induced by the cutting forces, indeed, impacts on the actual depth of cut, introducing form errors, potentially leading to scraps or unacceptable defects [2]. This issue is critical for flexible components (e.g., slender shafts), since significant workpiece deflection could occur during machining. Therefore, the minimization of geometrical errors while maintaining high productivity entails generating a machining cycle based on both the component stiffness and the cutting forces (i.e., the cutting parameters and workpiece material). The simplest approach that could be pursued to achieve such goal is based on trial-and-error procedures, that often reflect in uncertain manufacturing lead times. Moreover, this method gets less acceptable as the batch dimension decreases and the material cost increases, and it does not ensure the selection of an optimal solution, feasible only by getting a deeper understanding of the process behavior.

Digital Twin (DT) of machining processes can be exploited to reach such a goal [3]. DTs are virtual replica of a physical entity that could be used to analyze the process and make decisions through interaction between physical and virtual world. In the specific case a DT that includes cutting mechanism is required [3]. In this context, Zhu et al. developed a DT for machining process of thin-walled parts [4], while Afazov and Scrimieri focused their work on chatter vibrations [5]. This work presents a mechanism model for turning of slender workpiece that allows deflection compensation and could potentially enable the development of a Digital Twin when connected with the physical world (e.g., machine tool sensors).

On one side, the cutting forces can be estimated by means of simplified models based on cutting conditions, tool geometry and material proprieties [1]. The most adopted approach is taking advantage of mechanistic force models, tuned using experimentally identified cutting force coefficients [6]. In turning such an approach is generally used to compute the cutting force (in the cutting speed direction) and the rake face force. If decomposition of rake face force on feed and depth directions is required, as in the case of deflection estimation, chip flow angle needs to be computed. The simplest and most used approximation of such angle can be obtained by using the formulation proposed by Colwell [7].

On the other hand predictive models of workpiece deflection have been proposed for turning of slender shaft [8–10] The most effective methods are based on numerical analysis [2,11] (Finite Element Method, FEM), that is nowadays a commonly used tool, but requires specific high level knowledge and expertise.

This work presents the DRITTO (Deflection Reduction In Turning by Toolpath Optimization) project that aims at developing a digital solution for turning of flexible components with the purpose of generating optimized toolpaths to minimize geometrical errors, compensating the workpiece deflection. First the paper presents the proposed digital solution, describing the different blocks in which is composed. The numerical analyses involved in the toolpath optimization process are simplified to make their automation feasible and time effective. Cutting forces are estimated using a mechanistic force model and using Colwell formulation for chip flow. Workpiece behavior is modeled using Timoshenko beam model, its generation and update during the machining process are automatic, only toolpath and stock geometry are needed. Second, experimental validation is presented, specific tests were carried out of simplified case studies focusing on roughing operations, where geometrical errors are relevant, and the machined geometry could affect the subsequent phases (i.e., semi-finishing and finishing). Finally, conclusions are drawn, and future activities described.

Proposed digital solution

The proposed digital solution in schematized in Fig. 1. At the background level, the digital solution will include a toolpath generation model that will be interfaced with a simplified FEM environment to simulate the workpiece behavior under the effect of cutting forces. The system is composed by three modules: a) workpiece FE modelling, b) turning process modelling, c) toolpath optimization.

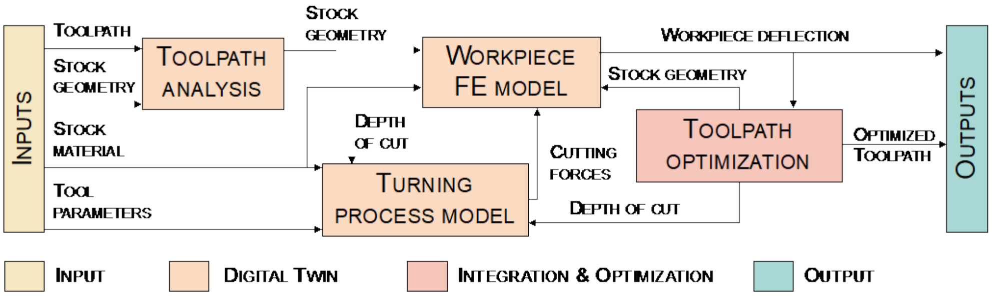


Fig. 1 General overview of the DRITTO digital solution.

The modules will be configured as an integrated solution: only the stock geometry and material, toolpath and tool geometry will be needed. The innovative idea underpinning the DRITTO solution is to fully integrate the workpiece deflection predictive model, so that the toolpath computation can be performed considering workpiece compliance changing during the turning process, as effect of material removal, and the instantaneous cutting conditions.

Input. The proposed approach requires the toolpath and the stock to compute and update the actual geometry of the workpiece and estimate the actual depth of cut. Toolpath is input as a standard ISO code (i.e., G Code), from which the system extracts the actual toolpath and the cutting parameters (i.e., cutting velocity and feed). The toolpath is then discretized to analyze the process with the desired resolution.

Stock geometry is included as a text file, written in a specific format: starting from tailstock (or free end) of the workpiece the segments with continuous radius variation along the axis are identified. Each segment is characterized by outer and inner radius at both its ends and by its length, hence every line of the text file represents one segment. Text file is reporting five different values for each line: initial outer radius, initial inner radius, final outer radius, final inner radius, length of the segment. This approach allows to represent any axisymmetric workpiece geometry. Portion inside the chuck should not be included in this representation.

In addition to these two inputs, tool geometry and workpiece material data are required. For the tool, lead angle and corner radius are needed, while for the workpiece material both elastic material proprieties (i.e., Elastic Modulus and Poisson Ratio) and cutting force coefficients should be input.

Turning process model. The cutting force model implemented in this work is provided below:

$$F_t = K_{tc}bh + K_{te}b \qquad F_{rf} = K_{rfc}bh + K_{rfe}b \tag{1}$$

$$F_f = F_{rf}\cos(\Omega) \qquad F_{ap} = F_{rf}\sin(\Omega) \tag{2}$$

where F_t is the cutting force in the cutting speed direction, while F_{rf} on the rake face plane, decomposed in feed force (F_f) and depth of cut force (F_{ap}), K_{ic} are the cutting force coefficients and K_{ie} the edge coefficients, b is the contact length and h is the chip thickness, Ω is the chip flow angle. In this work the Colwell approximation for such angle was used [7].

Workpiece FE model. Workpiece deflection is estimated by applying predicted cutting forces on a FE model of the component. Since slender workpieces are the target of the proposed approach Timoshenko beam 1D model [12] was selected as modeling strategy. A dedicated algorithm was implemented starting from the workpiece geometry to create nodes distribution (i.e., mesh) and element stiffness matrices, then assembled in the unconstrained component stiffness matrix K (Fig. 2). At each machining step the geometry is updated, and stiffness matrix reconstructed.

Constrained stiffness matrix is obtained by considering boundary conditions of chuck and tailstock (if present). In this work constraints are not considered rigid, therefore a 6x6 diagonal stiffness matrices are adopted as follows:

$$K_{chuck} = diag(K_{xc}, K_{yc}, K_{zc}, K_{rotxc}, K_{rotyc}, K_{rotzc}) \tag{1}$$

$$K_{tail} = diag(K_{xt}, K_{yt}, K_{zt}, K_{rotxt}, K_{rotyt}, K_{rotzt}) \tag{2}$$

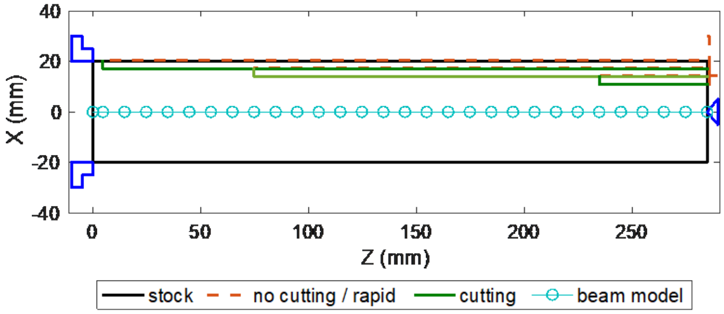


Fig. 2 Stock and toolpath example.

where diag() is the diagonal matrix that is characterized on its diagonal by the values provided in the bracket and K_{ij} are the stiffness value on the i degree of freedom for the j constraint. K_{chuck} is then assembled to the unconstrained matrix K by adding such matrix to the last node, while K_{tail}, if present, is assembled to the first node (i.e., end of the workpiece).

Toolpath optimization. Using the predicted cutting forces and the proposed modeling strategy it is possible to estimate workpiece deflection during the process by performing static analysis at each step. An iterative approach was used to consider the actual workpiece geometry and depth of cut: first the deflection was estimated using the commanded depth of cut, such first-attempt deflection was used to update both workpiece geometry and depth of cut, and a new deflection was evaluated, such cycle was repeated until convergence (minimization of the error on predicted deflections). Workpiece deflections are then used to compute the effective machined geometry (i.e., the effective workpiece radius, R_{eff}) as follows:

$$R_{eff} = \sqrt{(X - dx)^2 + dy^2} \tag{3}$$

where X is the commanded motion of the tool (i.e., desired radius), dx is the deflection on depth of cut direction and dy is the deflection on the cutting direction. Starting from such values, compensated toolpath is derived and written in a new file using ISO standard.

Integration. The different modules are integrated by exchanging data as highlighted in Fig. 1. Toolpath analysis computes depth of cut and workpiece geometry at the different steps of the machining operations, the first is input to the process modules to predict cutting forces, while workpiece geometry is essential for the beam model generation. Cutting forces are applied to such model to predict deflection. The first prototype of the digital solution was developed in MATLAB.

Experimental results

An experimental validation of the proposed approach was carried out at Meccanica Ceccarelli & Rossi facility. Turning operations were performed on a CNC lathe Mori Seiki SL-2500Y, equipped with a dynamometer (Kistler 9257A) to acquire cutting forces (Fig. 3).

Case studies. The proposed approach was tested on different geometries, using the same tool and material (C45 Steel). A Sandvik Coromant CNMG 120408-PM 4425 insert was used (corner radius 0.8 mm), mounted on a T-Max toolholder P DCLNL 2525M 12 (lead angle -5°). Four case studies were machined starting from a 40 mm bar: three simple single diameter cylinders (analyzing a single pass) and one shaft with three different diameters (analyzing three subsequent passes), their geometries are shown in the figures (Fig. 4, Fig. 5, Fig. 6, Fig. 7). Tailstock was used for all the case studies.

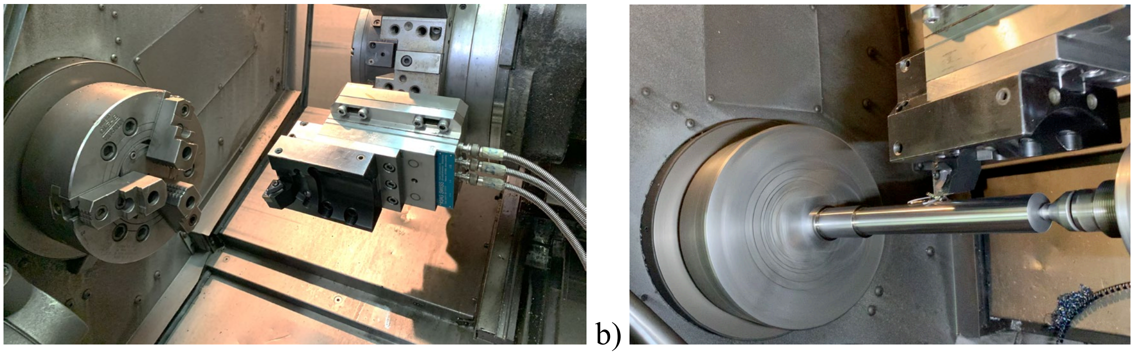
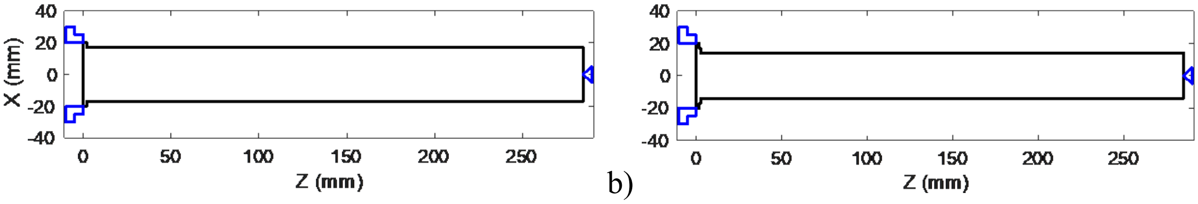
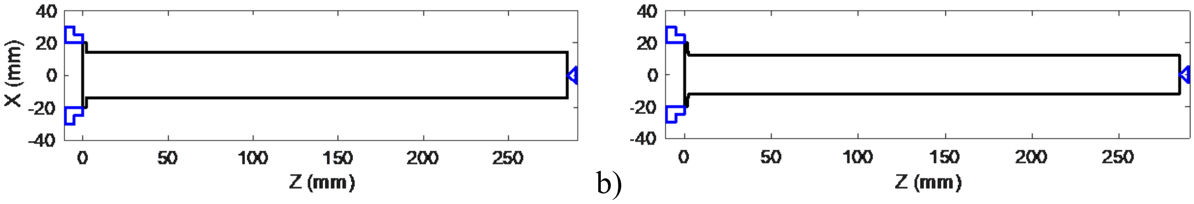

a) b)

Fig. 3 a) experimental set-up b) turning of a case study.



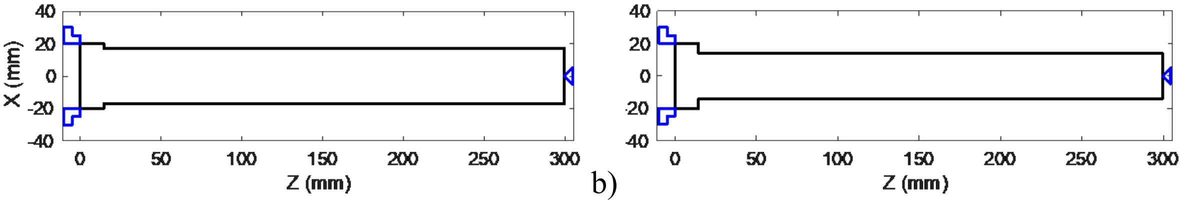
a) b)

Fig. 4 Case A (overhang 287.5 mm) a) stock D: 34 mm b) final D: 28 mm.



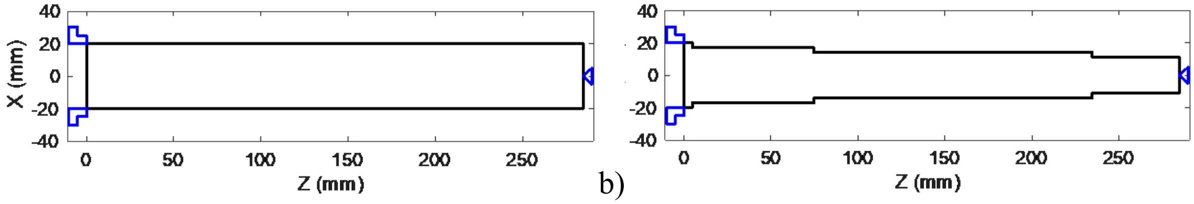
a) b)

Fig. 5 Case B (overhang 287.5 mm) a) stock D: 28 mm b) final D: 24 mm.



a) b)

Fig. 6 Case C (overhang 299.5 mm) a) stock D: 34 mm b) final D: 28 mm.



a) b)

Fig. 7 Shaft (overhang 287.5 mm) a) stock D: 40 mm b) after 1st pass D: 34 mm L: 280 mm, 2nd pass D: 28 mm L: 210 mm and final pass D: 22 mm L: 50 mm.

Roughing operations were investigated using 200 m/min cutting velocity, feed 0.2 mm/r and radial depth of cut 2 mm (case study B) and 3 mm (all the other case studies).

Cutting forces. Cutting force coefficients were identified for the specific tool-material couple performing preliminary tests, acquiring cutting forces and using the procedure reported by Altintas [1], results are summarized in Table 1.

Table 1 Cutting force coefficients

K_{tc} [MPa]	K_{te} [N/mm]	K_{rfc} [MPa]	K_{rfe} [N/mm]
1748.5	99.2	703.0	92.5

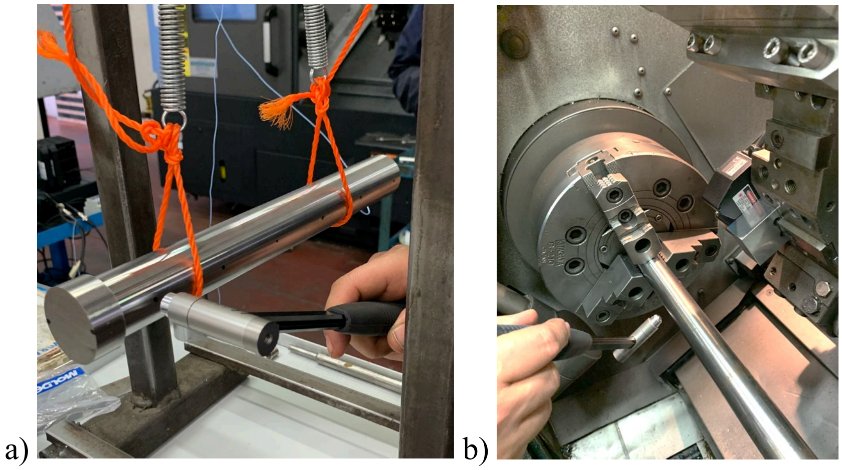


Fig. 8 Impact testing a) free-free boundary condition b) constrained.

Workpiece. To test the proposed approach without the uncertainties of material proprieties and constraints stiffnesses, some preliminary tests were performed to tune such values. Free-free modal analysis on bar specimens was carried out to identify material properties (Fig. 8a) through impact testing. Typical steel values were identified: Young Modulus: 210150 MPa, Poisson Ration: 0.28.

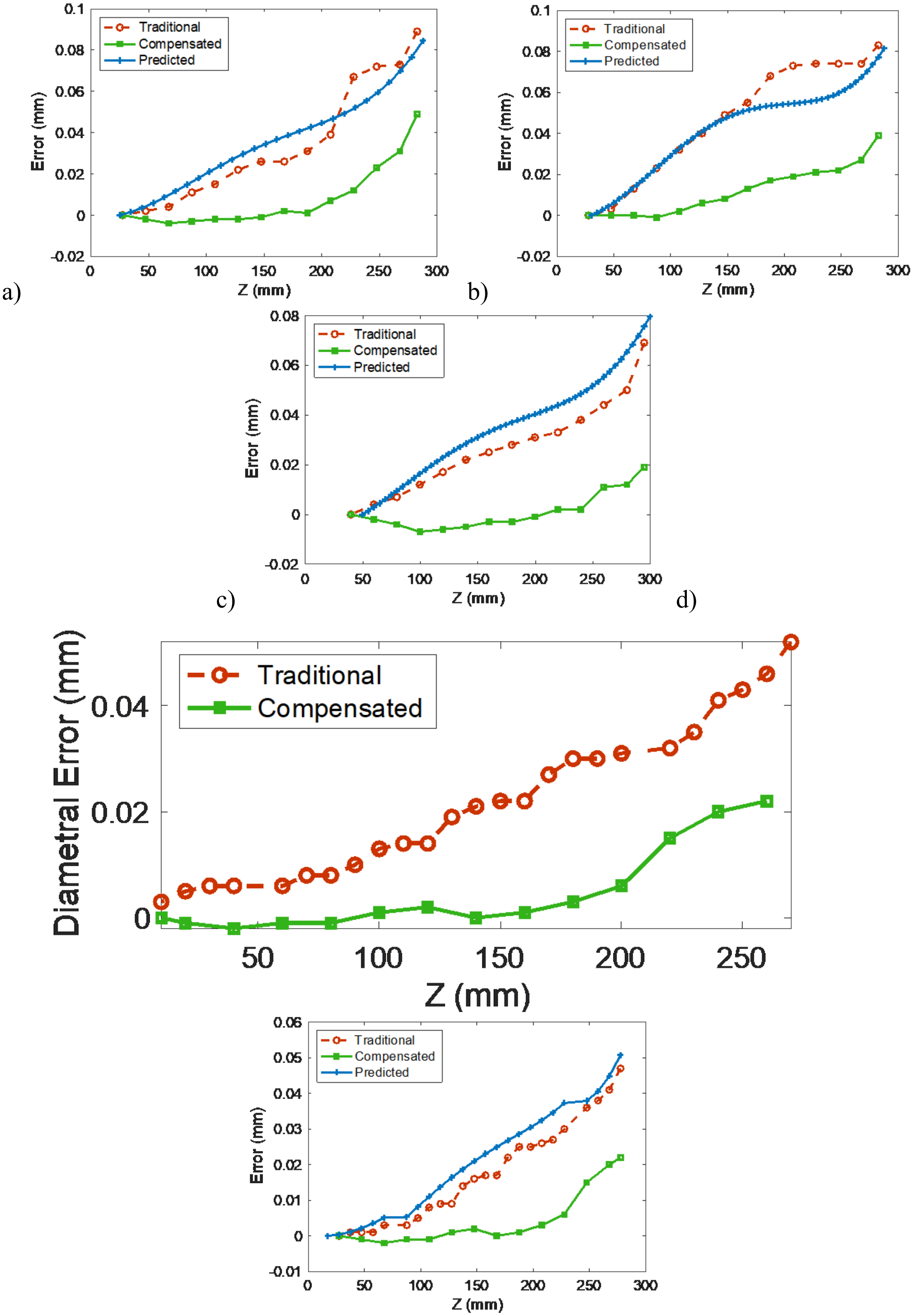
In addition, experimental modal analysis in the constrained configurations was used to estimate chuck and tailstock stiffnesses (Fig. 8b). Results are presented in Table 2. The chuck was modeled as a fixed end, while tailstock as a pinned end (i.e., free rotations).

Prediction results. To investigate the effectiveness of the proposed solution in estimating the machined workpiece geometry, a comparison between predicted and measured diametral errors was carried out and shown in Fig. 10. Results show good agreement between measured and predicted values, especially in terms of overall error difference between tailstock and chuck (average deviation on predicting the errors of 6.0, 5.4, 4.7, 4.1 µm in case studies a, b, c and shaft respectively). However, some discrepancies are found in the error shape, probably due to the tailstock modeling. Indeed, it is worth to point out that in the tested scenarios, the tailstock stiffness plays a crucial role in determining the error.

Toolpath compensation. The proposed approach was then applied to compute the compensated toolpath for all the case studies and machined geometries were measured for both compensated and non-compensated toolpath to evaluate its effectiveness. Results are shown in Fig. 10. As clearly emerges from the results, the compensated toolpath has proven to be effective in drastically reducing the errors, by at least halving the maximum error and by smoothing the shape. The average reduction achieved was about 62%, 74%, 68%, 72%. in case studies a, b, c and shaft respectively.

Table 2 Constraints stiffnesses

	Kx / Ky [N/mm]	Kz [N/mm]	K rotx / K roty [N mm/rad]	K rotz [N mm/rad]
Chuck	3.30e4	1e15	6.87e7	3e7
Tail	5.50e3	1e15	0	0



a) b) c) d)

Fig. 9 Comparison between predicted and measured diametral errors and measured values with compensation strategy on: a) case study A, b) case study B, c) case study C, d) shaft.

The overall error appears to be well-compensated until the area close to the tailstock. This is probably due to local effects of tailstock constraints and the non-modelled impacts of the cut entry. These aspects need to be further investigated to improve the solution. However, even in this part the reduction achieved was significant: about 45%, 53%, 50%, 55% in case studies a, b, c and shaft respectively.

Conclusions

The DRITTO project aims at developing a tailored solution for the computation of optimized toolpaths for turning of slender workpiece. The project is still ongoing, and an intermediate validation phase has just concluded. The solution developed is composed of different modules that have been, at the current stage, individually validated. The prediction of workpiece deflection, based on simplified FE models and cutting forces estimation, has shown to be adequate accurately in estimating the overall shape errors. Further activities will be focused on investigating alternative constraints modeling strategy for the tailstock to considering local effects and improve the prediction accuracy. Such predictive module was exploited to compute the compensated toolpath through a dedicated approach and results confirm that providing an accurate prediction of the shape error could represent an effective approach for its reduction. The experimental validation shows that the error is globally reduced by at least half compared to the non-compensated tests. Such results were consistent for all the case studies investigated.

Although some residual errors could be highlighted approaching the tailstock, even at the current stage the solution seems promising in drastically reducing the shape error in roughing operations which could be exploited to avoid the need of semi-finishing phases, in line with the goal of the DRITTO project.

Further developments will be focused on:

- Investigating the effects of the tailstock constraints.
- Extending the validation to finishing operations.
- Studying the potential synergies with machine tool sensors to build an actual DT.
- Developing a Graphical User Interface for the implementation of the solution in the SME manufacturing environment.

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