Integration of Machining Process Digital Twin in Early Design Stages of a Portable Robotic Machining Cell

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Abstract. Industrial robots have been getting a more important role in manufacturing processes during the last decades, due to the flexibility they can provide in terms of reachability, size of working envelope and workfloor footprint. An especially interesting application are material removal processes and specifically machining. Use of robots in machining has opened new pathways for the development of flexible, portable robotic cells for several use cases. However, the peculiarity of such cells compared to traditional machine tools calls for novel approaches in their design and dynamic analysis. To this end, this work proposes an approach that integrates the digital twin of the machining process to set the boundary conditions for the design and dynamic analysis of the robotic cell. Physics-based modelling of milling is coupled with a Multi-Body Simulation of the robotic arm to define the inputs for the design of the cell. The design and dynamic analysis of the robotic cell is performed in a commercial FEA package, taking into account the requirements of the machining process.

Keywords: Robot machining · Digital twin · Modal analysis · Harmonic response

1 Introduction

Industrial robots have been an integral part of the manufacturing sector since several decades. Lately, they have upgraded their role and are directly involved in manufacturing processes, forming the base structure of manufacturing cells for several processes, one of which is machining [1]. Machining with robots is an interesting opportunity due to the ability to machine large scale parts with complex geometries in single operation setups, thanks to their wide working envelopes and flexible kinematics [2].

Together with the introduction of machining with robots, another application that has emerged as well is the use of robots for hybrid manufacturing. Hybrid manufacturing, which combines additive and subtractive processes on a single workstation, has drawn significant attention due to its ability to capitalize on the advantages of independent processes, while minimizing their disadvantages [3]. Reduced production times, desirable geometric accuracy and surface characteristics, multiple material parts, and the ability

to repair damaged parts are some typical advantages coming with the use of hybrid manufacturing [4]. The use of robots for hybrid manufacturing is a much more flexible alternative compared to hybrid machine tools, in terms of integration complexity and, as a result, it has been highly pursued [5].

Hybrid manufacturing also opens a pathway for in-situ repair of high-value industrial components for industries, such as aerospace, oil and gas, etc. [6]. A portable robotic cell for repair enables the solution to move to the problem, instead of the opposite that was the norm for years [7]. Through portable manufacturing cells, supply management practices, such as just-in-time manufacturing, can achieved. The waste is eliminated in terms of time, inventory, transportation and the supply chain of a production or maintenance operation could be shortened [8]. Apart from significantly shortening the supply chain, utilizing in-situ repair methods for large-scale industrial components can dramatically increase the sustainability of the repair operation, by significantly reducing the required transports [9].

Although the development of portable manufacturing cells based on hybrid manufacturing robots are a promising solution for in-situ manufacturing and repair, the design of the load bearing structure of the cell becomes significantly complicated, since it needs to provide the required stiffness to support the machining loads, while minimizing the weight to enhance portability. The load bearing structure cell is an essential functional component inside the machining system. The final accuracy of the machining system depends on the behavior of the frame structure which is loaded under static, dynamic, and thermal loads [10]. To support this design optimization effort, the digital twins of the machining process can be exploited, taking into account both the process and the robotic arm to set the boundary conditions for the design of the load bearing structure.

2   Literature Review

The use of the digital twins of the process to support the design and development of the machining system has been explored in literature, in several applications that are mainly related to high-accuracy manufacturing processes. Huo et al. [11] have proposed an integrated dynamic design and modelling approach for the development of a micro-milling machine. By integrating the modelling of the micro-milling process and the dynamic models of the sub-components of the machine, they managed to quantify the impact of their design in the accuracy of the process and take it into account in the optimization of the design. The importance of the digital twins of the process during the virtual prototyping phase of machine tools has been also highlighted by Altintas et al. [12], who introduced the virtual machine tool concept that comprised of Finite Element modelling of the machine tool components, kinematic modelling of the machine tool, Multi-Body Simulations, as well as dynamic modelling of the cutting process. Leonesio et al. [13] proposed a set of process related KPIs, targeting process quality and economic efficiency, which can be integrated in the machine tool design process to deliver the optimal product for a specific application. Regarding portable equipment, Law et al. [14] have developed a dynamic substructuring framework for in-situ machining systems to predict the dynamics of the assembled machine tool-workpiece system and facilitate the design of portable machine tools, enabling also the identification of their position-dependent

dynamics [15]. Checchi et al. [16] have proposed a stiffness identification methodology for portable machine tools and offline compensation of their deflections, with a focus on machining of wind turbine components. Garnier et al. [17] have investigated the stability of the mounting structures of mobile machining robots, focusing on naval applications. In the field of robotics, Hazel et al. [18] developed a portable, track-based robot for in-situ repair of hydropower equipment through welding and grinding. By using the dynamic model of the grinding process, they were able to develop a robotic platform that would ensure the required quality of the processed surface. There have been some additional solutions proposed for portable manufacturing cells, either based on portable platforms [19] or mobile robots [20]. Apart from the research related to portable robotic cells for machining, there are also industrial efforts for such solutions that can be transferred to remote or harsh environments and operate [21]. This indicates the need for concrete developments that can support the design on such platforms.

Based on the literature review, it can be concluded that a gap exists on the development of portable machining solutions, based on robotic platforms, from the perspective of having an integrated representation of the interrelation between the machine and the process and being able to explore this during the design phase of the portable robotic cell. To this end, this paper presents an approach for the design, analysis and development of such systems, based on the integration of the digital twin of the machining process to facilitate design optimization.

3   Approach

The whole approach is based on the integrated machine-process modelling concept. In order to set accurate and realistic boundary conditions for the dynamic analysis of the load bearing structure of the robotic cell it is important to know the input loading conditions. These loading conditions are dependent on the physics of the machining process, as well as the dynamic behavior of the robot during the process. This calls for the formation of the robot machining Digital Twin that will act as an input for the robotic cell design. The formation of this Digital Twin is based on the integration of previous works of the authors. The Multi-Body Simulation (MBS) of the machining robot captures its dynamic behavior during the process [22], where the cutting forces that are exerted during the machining process are used as an input. The cutting forces are modelled with the mechanistic modelling approach. The specific force coefficients required for this model (that is explained in detail in the next section) can be constantly captured by indirectly monitoring the cutting forces during the robot machining process [2], thus closing the loop with the simulation and forming the Digital Twin. The Digital Twin architecture is depicted in Fig. 1.
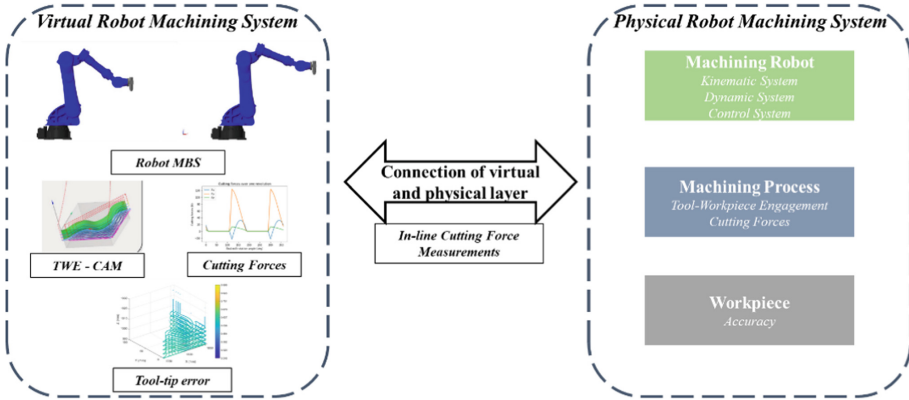
Fig. 1. Robot machining digital twin architecture

The whole approach of integrating the robot machining Digital Twin in the whole design of the cell is presented in detail in the next sections, while Fig. 2 provides an overview of the approach.
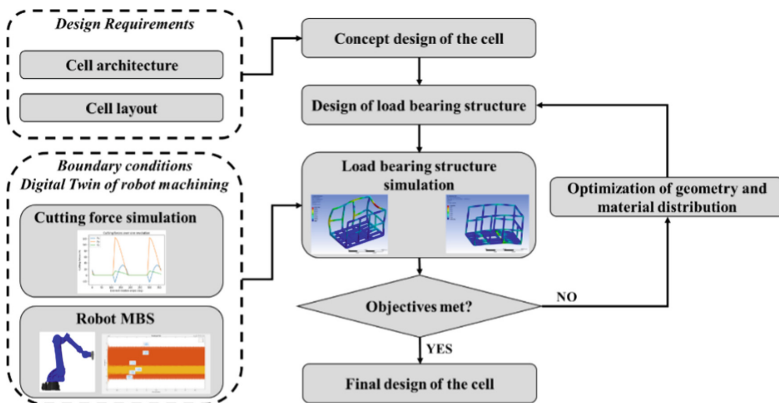

Fig. 2. Overview of the proposed approach

3.1 Simulation of the Milling Process

The first step of the whole approach is the determination of the cutting forces that will take place during the machining process. For this purpose, the well-established mechanistic cutting force model of Altintas and Lee [23] is utilized, which provides a fast and flexible modelling approach that takes into account the tool geometry and material, process parameters, workpiece material data and tool orientation. Moreover, the amplitude of specific force coefficients regarding different cutting tools and materials that are available in literature provides an opportunity for a vast design space exploration

regarding different machining operations that the robot will have to serve. In short, this model considers the cutting forces to be linearly linked with the feed per tooth (f_z) and axial depth of cut (z), while being a function of the immersion angle of the j-th cutting edge of the cutting tool (φ_j). The cutting force coefficients ($K_{.c}$) and edge force coefficients ($K_{.e}$) are experimentally determined or they can be sourced from related literature. The formulation of the cutting force model is presented below.

$$\begin{cases} dF_{t,j}(\varphi_j, z) = K_{te}dS(z) + K_{tc}f_z\sin(\varphi_j)dz \\ dF_{r,j}(\varphi_j, z) = K_{re}dS(z) + K_{rc}f_z\sin(\varphi_j)dz \\ dF_{a,j}(\varphi_j, z) = K_{ae}dS(z) + K_{ac}f_z\sin(\varphi_j)dz \end{cases} \tag{1}$$

The instantaneous cutting forces in the tangential ($dF_{t,j}$), radial ($dF_{r,j}$) and axial ($dF_{a,j}$) direction are integrated along the axial depth of cut to calculate the cutting forces at each cutting edge over one revolution of the tool. The results of this first simulation are then fed as an input to the robot Multi-Body Simulation that is presented in the next section.

3.2 Robot Multi-body Simulation

After the loading that is introduced by the material removal process is calculated the next step is to determine the impact of this load on the dynamic response of the robotic arm, in order to use it as an input for the dynamic simulation of the cell. For this purpose, a Multi-Body Simulation (MBS) of the robotic arm is utilized. The MBS considers both the flexibility of the joints and the links of the robot.

The joints are modeled as 1 Degree-of-Freedom (DoF) revolute joints with a spring-damper system along the rotation direction to capture the elastic deformation of the joints due to the machining loads.

For the modeling of the links the Component Mode Synthesis (CMS) method is utilized. This is an effective method to reduce the complexity of the model, while preserving the true static and dynamic behavior of the links. The Finite Element (FE) model of the links is developed and the interface points (i.e., the mating surfaces with the joints of the previous and next link) are defined. Next, the Craig-Bampton method is used to build the reduced order model of each link. From the full order FE model, only the interface DoFs are preserved, as well as some DoFs that are necessary to calculate the vibration modes of the link with a clamped-clamped boundary condition. As a result, the Craig-Bampton method retains both the static and vibration modes of the link and dramatically reduces the DoFs of the model, thereby its computational requirements. The result of this method is the creation of the so-called Superelements, which are comprised of the reduced mass and stiffness matrices of each link.

Finally, the superimposition of the joints and links models enables the development of the MBS that calculates the dynamic behavior of the whole robot during machining. By importing the pre-calculated cutting forces in the MBS, it is possible to estimate the final loads that will be transferred to the base of the robot and, ultimately, on the load bearing structure of the portable cell. These loads are utilized as an input for the next step of the analysis, which is the determination of the dynamic behavior of the cell. Figure 3 provides an overview of the robot MBS approach.
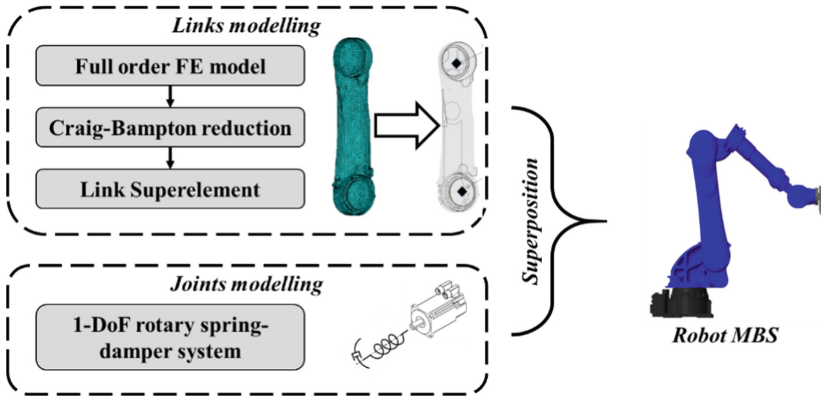
Fig. 3. Overview of the robot multi-body simulation

3.3   Simulation of the Robot Machining Cell

The final step of the whole approach is the determination of the structural and dynamic behavior of the load bearing structure of the portable cell. There are three key objectives that need to be fulfilled in order to create a successful design that will ensure a safe and reliable operation and transportation.

1. The load bearing structure of the cell should be able to withstand its own weight during transportation. For this purpose, a static analysis has been setup to ensure that the stresses during transportation are within the elastic limit
2. The deflections of the load bearing structure should be such, so that they do not impair the accuracy of the process. Ultimately, the main criterion to address this objective are the deflections between the mounting points of the robot and the mounting points of the workpiece. These can be determined through a harmonic response analysis. Since the loading during the milling process is harmonic, due to the intermittent cutting, the harmonic response analysis is a suitable tool to calculate the dynamic response of the cell in the whole frequency range of interest, which is determined by the capabilities of the machining spindle.

Based on the results of these three simulations a design of the load bearing structure of the cell can be performed, so that it is suitable for machining operations.

4   Case Study: A Portable Robotic Cell for Hybrid Manufacturing

The case study that has been selected to demonstrate the whole approach is for a portable robotic cell for hybrid manufacturing operations. The intended purpose of the cell is the in-situ repair and remanufacturing of industrial components. As a result, the main design requirements of the cell are: (a) a relatively low weight that can enable easy transportation between the different operating sites; (b) a dynamic behavior that will enable it to successfully complete milling operations; (c) manufacturability of the cell

should also be considered. The robot that will be utilized is a Yaskawa GP225 industrial robot arm, along with a Yaskawa DK-500 2-DoF table, which will offer an additional flexibility to the machining and Additive Manufacturing processes, due to its redundant DoFs.

4.1 Architecture of the Portable Cell

The key elements of the main structure that affect its final design are related mainly with the layout of the various subsystems that is determined by the functional requirements of the cell. First of all, there is a need for two entrance points (one in the front and one in the side of the cell) to enable ingress and egress of the operators, as well as loading and unloading of the workpieces. Moreover, in the rear side of the cell, a shelf with an enclosure should be integrated, where the tools and process heads can be stored, when they are not in use. A retractable roof is installed on the top of the cell, so that it can be removed during transportation. Finally, a detachable platform where all the auxiliary equipment is stored (controllers, laser source, etc.) is installed on the rear side of the cell. All of these elements, dictate the areas where material can or cannot be placed in the load bearing structure, thereby affecting its design. Figure 4 provides an overview of the whole design.
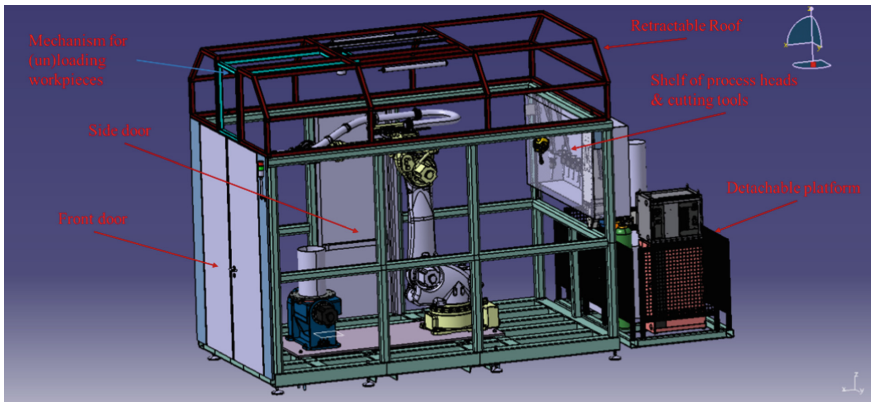

Fig. 4. Overview of the portable cell architecture

4.2 Concept of the Load Bearing Structure

The part that is of interest for the simulation is the part that actually affects the machining process, due to its dynamic behavior. So, the load bearing structure can be isolated for further analysis and optimization of its design. As mentioned previously, the manufacturability of the cell is one of the key design requirements. Therefore, a welded construction based on square beams has been selected for the load bearing structure. Moreover, two C-section beams are welded on the bottom side of the load bearing

structure in such a distance that will enable the transportation with a forklift. Shows the concept of the load bearing structure. Finally, vibration cancelling mounts have been selected two support the cell. Figure 5 provides an overview of the load bearing structure.
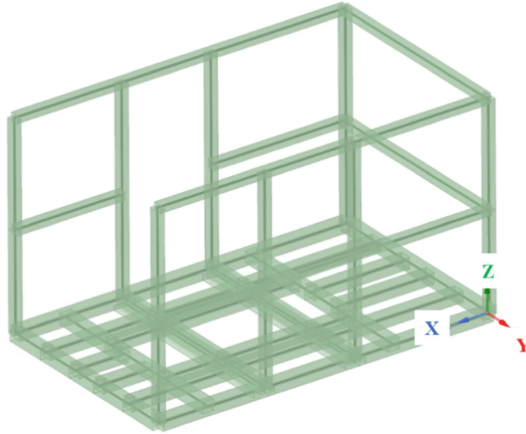
Fig. 5. Concept of the load bearing structure

4.3   Cutting Force Calculation

The milling processes that the robot will need to serve are mainly post-processing of Additive Manufactured components. In most applications where Additive Manufacturing is used for repair of industrial components, the target material is either a hardened steel or Heat-Resistant Alloys (HRAs). One of the HRAs that presents especially low manufacturability, leading to high cutting forces, is IN718. Moreover, IN718 is a very common material for Additive Manufactured parts. Therefore, in this case study milling of Additive Manufactured IN718 was considered. Based on the specific force coefficients for this specific material [2] the cutting forces that were calculated as a worst-case scenario with aggressive process parameters (Table 1) were $F_x = 1650N$, $F_y = 3130N$ and $F_z = 230N$.

Table 1.   Process parameters for worst-case scenario

| Process parameter	Value
Cutting tool diameter [mm]	50
Axial depth of cut [mm]	5
Radial depth of cut [mm]	45
Cutting speed [m/min]	450
Feed per tooth [mm]	0.16

4.4 Dynamic Behavior of the Robot

Next, the cutting forces were used as an input in the MBS of the robot to calculate its dynamic response. In order to also take into account the effects of the robot posture on its overall dynamic response, a large part has been designed and simulated, in order to evaluate the dynamic response over the whole toolpath (Fig. 6).
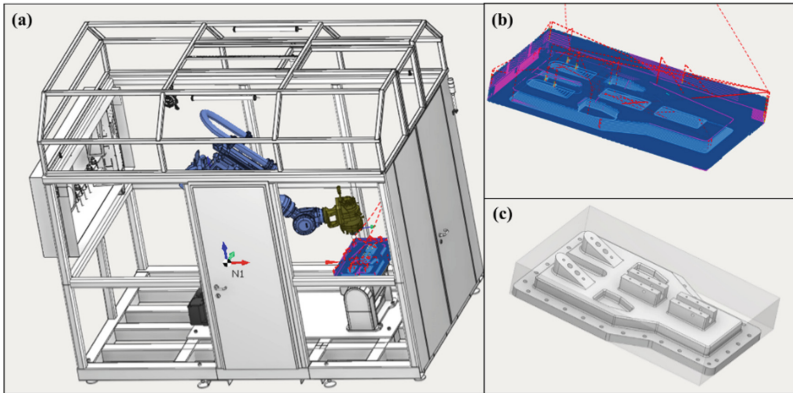
Fig. 6. (a) Toolpath used to evaluate the cutting forces; (b) close-up view of the toolpath; (c) close-up view of the workpiece and stock material
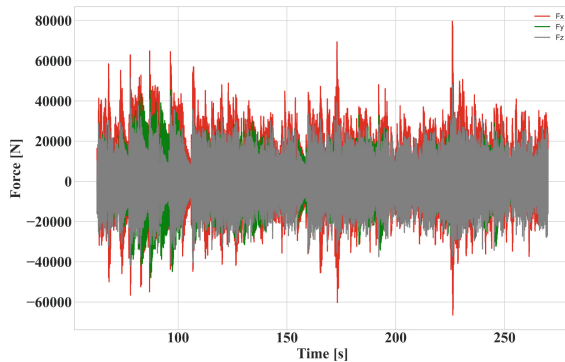
Fig. 7. Forces at the robot base during machining of IN718

Based on the results of the MBS the boundary conditions for the dynamic simulation of the cell can be determined. Figure 7 shows the MBS results regarding the forces at the base of the robot during machining of IN718. By identifying the amplitude of these forces, it is possible to create the input for the dynamic simulation of the cell.

4.5   Simulation of the Load Bearing Structure of the Portable Cell

Finally, the simulation of the load bearing structure of the portable cell can be performed. ANSYS Finite Element software has been utilized for this simulation. The grid that comprises the load bearing structure has been designed and the beams sections at each line of the grid have been inserted. Based on an iterative design process of simulation and re-design, 140 × 140mm steel square sections with 4mm wall thickness were used for the bottom part of the structure, whereas in the sides of the structure 100 × 100mm steel square sections with 4*mm* wall thickness were used.

For the first load case that was described in Sect. 3.3, the C-sections at the bottom of the structure were used as supports, restricting the movement of the cell on the negative Z-axis. The weights of the robot, table and auxiliary equipment were applied, as well as the weights of the structure itself. A static structural simulation was performed to estimate the stresses on the load bearing structure.

For the second load case, a harmonic response analysis has been setup. The force that was calculated from the MBS of the robot has been applied in the mounting points of the robot on the load bearing structure. Figure 8 shows the boundary conditions of the simulation. Based on the type of mounts at the different nodes of the structure, the appropriate restraint has been selected. For the nodes where simple mounts were used, the structure was considered simply supported (grey supports in Fig. 8), whereas for the nodes where the mounts are going to be anchored in the foundation of the floor, fixed supports were used (black supports in Fig. 8). The deflections between the robot mounting point and the table mounting point were monitored, in order to identify the effect of the dynamic behavior of the structure in the machining process.
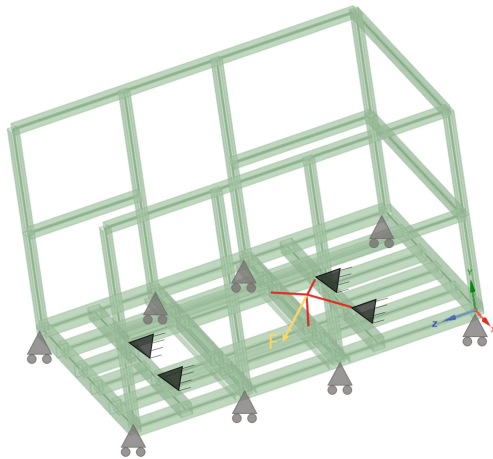
Fig. 8. Boundary conditions of the harmonic response analysis

5   Results and Discussion

The results of the static analysis are presented in Fig. 9. As it can be observed, the stresses on the structure are very low, indicating that the transportation of the cell can be performed without any issues.
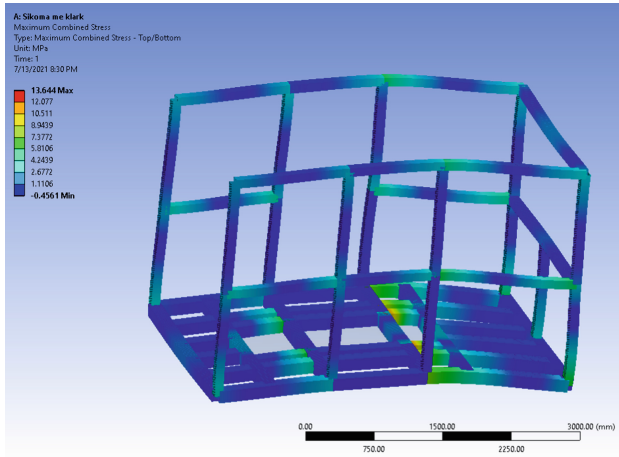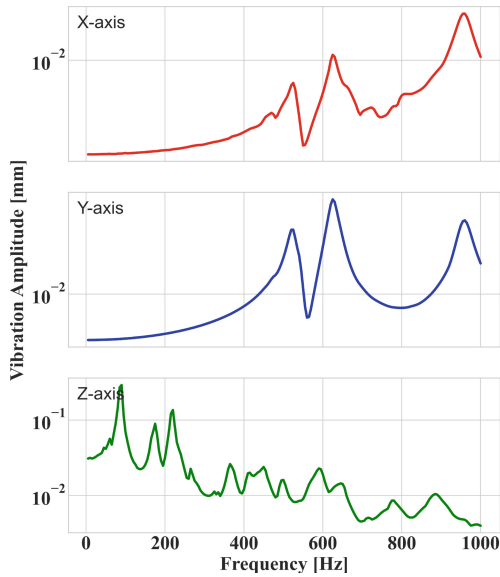

Fig. 9. Static analysis results

Fig. 10. Vibration amplitudes of the cell at the frequency range of interest

Figure 10 shows the semi-logarithmic plots of the vibration amplitudes over the frequency range of interest. As it can be observed, the main vibration component is that on the z-axis. This is something to be expected by the design of the load bearing component, since the beams are loaded in bending, due to the Z-axis component of the force, whereas in other two orthogonal axes they are loaded in tension-compression, where they present significantly higher stiffness (Fig. 11).

Table 2. Eigenfrequencies of the load bearing structure of the cell

Mode #	Frequency [Hz]	Mode #	Frequency [Hz]	Mode #	Frequency [Hz]
1	12.08	10	89.28	19	524.42
2	18.36	11	218.09	20	528.38
3	21.86	12	239.64	21	539.51
4	26.14	13	249.47	22	625.50
5	46.12	14	297.11	23	658.97
6	59.66	15	476.87	24	691.88
7	76.44	16	481.11	25	730.55
8	84.71	17	507.53	26	792.42
9	87.49	18	511.51		
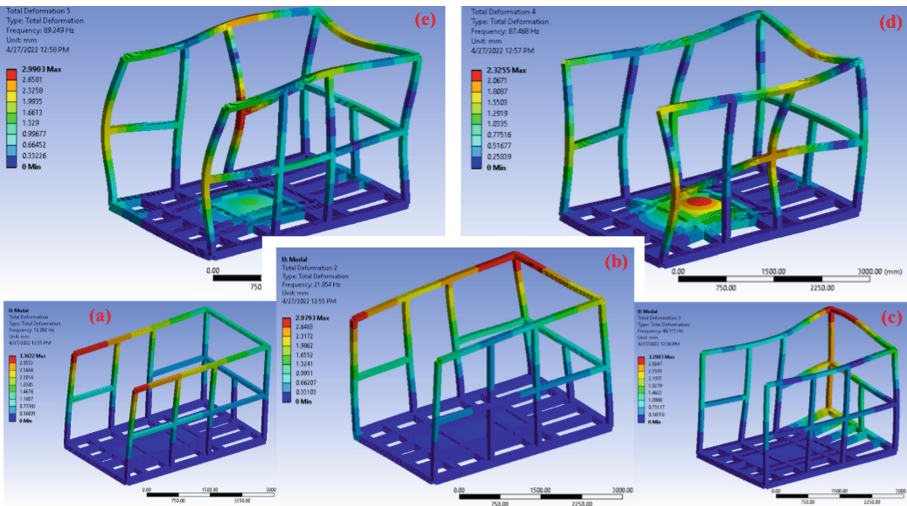
Fig. 11. Mode shapes of the 5 modes with the largest effective mass: (a) 12.08 Hz; (b) 21.86 Hz; (c) 46.12 Hz; (d) 87.49 Hz; (e) 89.28 Hz

The eigenfrequencies of the load bearing structure of the cell are presented in Table 2. Figure 12 depicts the mode shapes for the 5 eigenfrequencies that contain the largest

effective mass, according to the modal analysis. It is also important to pay particular attention at the loading frequency of 87.49 Hz, where the highest peak in the Z-axis vibrations can be observed. Figure 12 presents the vibration amplitudes of the whole cell at this loading frequency. It can be observed that the highest deformations can be found at the top horizontal beam on the rear side and the two vertical beams on the front side. Again, this is a result to be expected, since these two beams are the least supported in the whole load bearing structure. Nevertheless, such a deformation is not worrying since it will not interfere with the accuracy of the machining process. By examining closely the bottom of the structure and especially the mounting points of the robot and table, it can be observed that the deformation in those points is in the 10^{-2} mm range. Such a result is perfectly acceptable, given the fact that in order to achieve the cutting forces that were calculated in Sect. 4.3, a roughing operation should be implemented. In such a case, an accuracy loss in that range is not detrimental for the process.
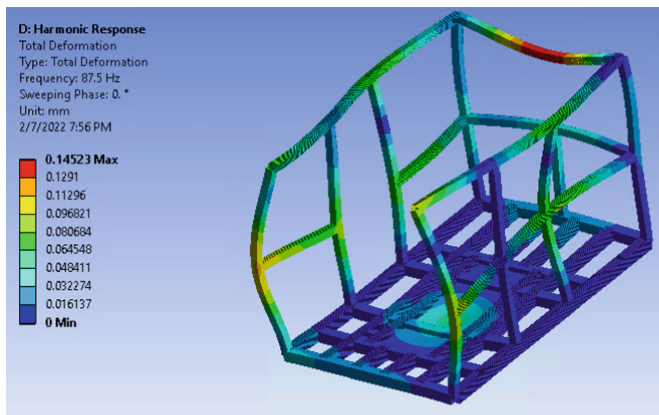

Fig. 12. Deformation of the cell at 87.5 Hz loading frequency

6   Conclusions

The scope of this work was to present an approach for the exploitation of the digital twin of the robot machining process, in order to design portable and structurally sound cells, towards in-situ repair and manufacturing. The whole approach consisted of an integrated machine-process modelling concept, where the machining process was firstly modelled, serving as an input for an MBS of the machining robot, which determined the boundary conditions for the simulation of the dynamic behavior of the robotic cell. Based on the results of the work the following conclusions can be drawn:

- The MBS of a machining robot can be a powerful tool during the design of its structural cell
- The use of the digital twin of the robotic machining process to build the boundary conditions of the simulation of the robotic cell can effectively lead to a virtual prototype

of the whole system that can reduce the need for physical prototyping and trial and error approaches

Future work should include the closure of the loop of this whole approach, where the effect of the dynamics of the portable cell are also taken into account in the MBS of the robot, yielding further accuracy in the whole simulation. Moreover, tools for automation and optimization of the design process should be developed, based on this digital twin approach, which will reduce the manual effort of setting and evaluating diverse simulations and can assist the engineers during the design phase. Finally, the validation of the actual dynamic behavior of the manufactured cell should be performed and used as a benchmark for the simulation.

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