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Programming of machine tools and robots for machining using STEP-NC in the era of Industry 4.0

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Abstract *This paper presents a method for applying the ISO 10303-238 (AP-238) standard for programming CNC machine tools and robots for machining operations. The method encompasses programming, simulation, and machining by machine tools and industrial robots as part of current and future research at the University of Belgrade Faculty of Mechanical Engineering. Application and validation of methodology for programming according to STEP-NC protocol are performed using available CNC machine tools and industrial robots, with the following tools: (a) commercial CAD/CAM software, (b) STEP-NC Machine software with configured virtual machine tools and virtual robots, as well as (c) developed translators for generation of G-code and/or robotic programming language. STEP-NC provides new opportunities to support high-level information from design to CNC controller. This implies further evolution of the CNC system they will act using STEP-NC standards as an interface between CAD and CNC in the era of Industry 4.0.*

Keywords *STEP-NC, Machine tools, robots for machining, virtual machines and robots, Industry 4.0*

1. INTRODUCTION

This paper discusses the programming of the CNC machine tools and industrial robots for machining, based on ISO 10303-238 (AP-238) known as STEP-NC (Standard for Product Model Data Exchange for Numerical Control) in the era of Industry 4.0. The article also presents research results at the Faculty of Mechanical Engineering from Belgrade on the application of a new programming method in actual production conditions.

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Industry 4.0 has an initiative that aims to digitalize industrial manufacturing via the exploitation of innovative technologies. The transformation goal is to enable and enhance the flexibility, individualization, and customization abilities of the production system. In order to meet the challenges of Industry 4.0, the current manufacturing system requires a significant transformation in the information handling between CAD/CAPP/CAM - CNC [1].

Machine tools have evolved from simple machines to today's highly sophisticated Computer Numerically Controlled (CNC) machine tools [2]. Much like the different stages of industrialization, machine tools have also gone through different stages of technological advancements. Industry 4.0 pleads for a new generation of machines-Machine Tool 4.0 [3,4]. Machine Tool 4.0, otherwise known as Cyber-

Physical Machine Tool (CPMT), is the integration of machine tool, machining processes, computerization, and networking, where embedded computers and networks can monitor and control the machining processes, with feedback loops in which machining processes can affect computations and vice versa [5].
In this new industrial world, everything will be connected through the internet and the cloud, enabling factories to function as a system rather than individual parts. Many jobs will shift from physically operating to operating them via computers, monitoring data, and providing monitoring to automated CNC machining operations [6].
Although the machine tools have changed rapidly, the programming language has basically remained the same with programming in G-code (ISO 6983) [7].
Machine tool programming by G-code is characterized by low-level information content. This low-level information describes elementary actions and tool moves, strongly reducing possibilities at the CNC level. It also breaks the CAD-CAM-CNC numerical chain and disables easily gathering feedback information from the shop floor [8].
It is necessary to prepare the tool path for each type of CNC machine tool individually using the appropriate postprocessor. It requires a large number of different postprocessors for each type of machine tool, Fig.1. Therefore, the classical programs for CNC machine tools (G-code) do not include any useful information about the product, such as data about the geometric primitives of the model, tolerances, material properties, setting up the fixture, and other information created during the design and planning of manufacturing technology. All this information will disappear when converting the tool path in G-code [2].
Today a new standard, STEP-NC, is being used as the basis for the development of the next generation of CNC controller. The new STEP compliant NC standard (STEP-NC) is based on the Standard for Exchange of Product data model (STEP) and has been developed to overcome the shortcomings of G-code [9].
In the field of machine tool programming, an open challenge is the new programming method based on STEP-NC standards, for different machining systems.
The STEP-NC provides new opportunities to support high-level information from design to CNC controller. It allows bi-directional data flow between CAD/CAM and CNC without any information loss, Fig.1.
STEP-NC is a new interface that has been developed for the exchange of information between CAD/CAM systems and CNC controllers, and various users who exchange technology or monitoring machining processes over the Internet, which is in line with Industry 4.0.

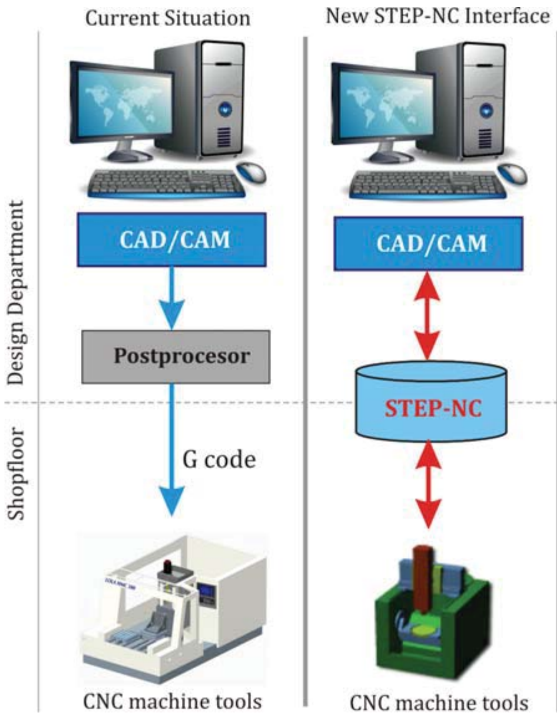

Fig. 1. Comparison of current G-code and new STEP-NC interface for programming CNC machine tools

In this regard, this paper will present the possibilities of applying the new programming method for different CNC machine tools (milling, turning, Wire EDM, additive manufacturing, CMM, etc.) and the example of robots for machining in the era of Industry 4.0.

2. STEP-NC LITERATURE REVIEW

The STEP-NC, as a new standard, provides a new breed of intelligence to the CNC controller in terms of interoperability, flexibility, adaptability, and extensibility [10].
The STEP-NC standard has been developed to challenge the standardization of the exchange of

product data along the manufacturing digital chain (CAD-CAPP-CAM-CNC), which includes simulation, optimization, and convert or export code capabilities, Fig.2.

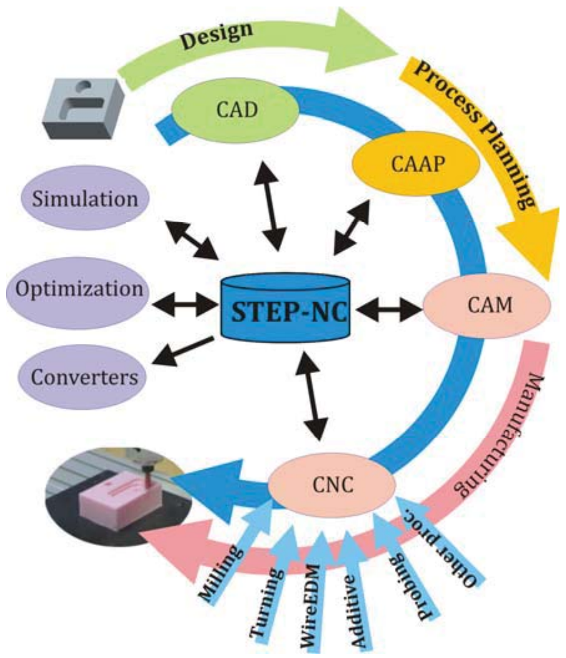

Fig. 2. Digital chains based on STEP-NC

Digital thread for manufacturing is considered for various CNC machine tools used in milling, turning, electro-erosion, additive manufacturing, and other processes, and also in machining operations where is used industrial robot. Many studies have been conducted to promote STEP-NC as an upcoming generation of data model interface for CNC systems.

The developing STEP-NC standards are the result of an international effort to replace the G-code ISO6983 standard with a modern associative language that connects the CAD design data used to determine the machining requirements for an operation with the CAM process data that solves those requirements [11].Thus the migration of G-code programming to STEP-NC calls for time, funding, and changes to the industrial mindset [8].

These new standards are ISO 14649 and ISO 10303-238. These standards can be viewed as two different implementation methods of the STEP-NC standard. The ISO 14649 standard is more likely to be used in an environment in which CAM systems have exact information from the shop floor, whereas ISO 10303-238, as a part of the STEP standard, is more suitable for a complete design and manufacturing integration [2].

The STEP-NC provides a comprehensive model of the manufacturing process. It is object and feature-oriented and describes the machining operations executed on the workpiece, and not machine-dependent axis motions. It will be running on different machine tools or controllers [12]. If old NC programs in G-code are to be used on such controllers, the corresponding translators or converters will be able to postprocess the STEP-NC program into different NC program types.

Due to the fluctuation in market needs and trends, digitization, data exchange between virtual companies around the world, CNC industrial companies are facing a big challenge to integrate all levels in product lifecycle management. In this regard, it can be said that the old method of programming using G-code, got an alternative in the powerful standard called STEP-NC.

2.1 Research project overview

The STEP-NC has been developed as a result of several research projects carried out by companies, university institutes, research institutes and associations, manufacturers of CAM systems, controls, and machine tools.

Different studies were carried around the world by major research groups which dealt with the application of STEP-NC for the integration of CAD, CAPP, CAM, and CNC systems. Within these studies the following projects are implemented [13,14]:

- European strategic program on research in information technology - ESPRIT STEP-NC.
- Intelligent manufacturing systems based on STEP-NC - IMS STEP-NC.
- Supermodel project – Model-driven intelligent control of manufacturing (MDICM).
- STEP manufacturing suite – SMS project,
- Rapid acquisition of manufactured parts – RAMP project.
- Intelligent manufacturing for STEP-supported machining and inspection.

One of the earliest international research projects is the European ESPRIT III project, OPTIMAL (Optimized Preparation of Manufacturing Information with Multi-Level CAM-CNC Coupling) for the development of

STEP-supported systems is the optimized preparation of manufacturing information with multi-level CAM-CNC coupling project which is based on information about features and machining strategies [13,14]. This project includes twenty industrial and academic partners with rich experience in the fields of CAD/CAM (Dassault, Open Mind), control (Siemens, OSAI), machine tools (CMS), and end-users (Daimler-Chrysler, Volvo) in Europe formed the European STEP-NC consortium [14].
The global research in the areas of STEP-NC has been primarily coordinated under a single IMS (Intelligent Manufacturing System) project that effectively entails an international package of actions. Partners from four regions participate in the project: EU, Korea, Switzerland, and the USA. The regional coordinators are Siemens (EU), CADCAMation (Switzerland), STEP Tools (USA), and ERC-ACI (Korea) [2,14].
The Super Model Project awarded in October 1999 to STEP Tools, Inc. (USA), working with a team of sub-contractors. It was a project funded by the National Institute of Standards and Technology (NIST). The goal of this project is to build a database that contains all the information required to make a part.
The result is STEP-NC as a modern, associative communications protocol that connects computer numerically controlled (CNC) process data to a product description of the part being machined. Integration of the CNC model into STEP to produce ISO 10303–238 was done in the United States, with the funding of the MDICM project by the NIST and led and work performed by STEP Tools, Inc. [15].
Results presented in this paper are based on ISO 10303-238, and software STEP-NC Machine. The STEP-NC Machine software can export files either in P21 (clear text) or P28 (XML). Used software STEP-NC Machine can export files in P21 (clear text) format that is currently the most popular implementation method, although P28 files, in format XML, are increasingly used today [16-18].

2.2 Levels of research strategies related to STEP-NC

STEP-NC promises new opportunities for machine tool programming, but also requires the development of the next generation of intelligent CNC systems [8,19]. Changes in the digital chain CAD-CAM-CNC are necessary, including high-level object-oriented information from STEP-NC files has to be interpreted and executed on the machine tool or robot axis commands.
Levels of research strategies, Fig.3, related to STEP-NC advanced programming is possible define at four levels [8,19,20]:

- At the first level, the use of STEP-NC with CNC controllers, which are only able to read only G-code files, by developing converters STEP-NC to G-code, is made possible. This level is indirect STEP-NC programming.

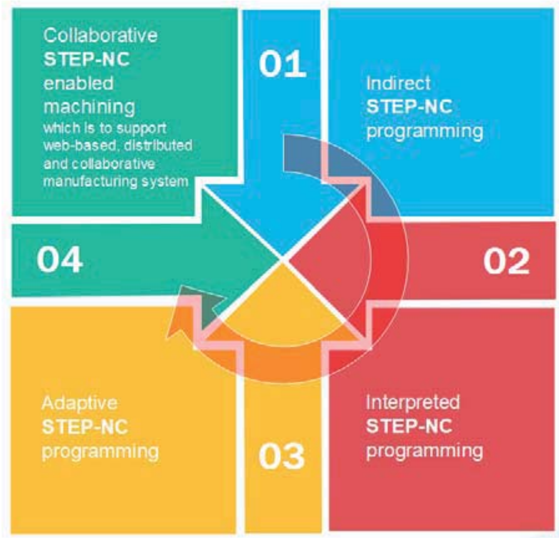

Fig. 3. Levels of research strategies related to STEP-NC advanced programming

- The second level is Interpreted STEP-NC programming where axis command is directly executed from STEP-NC file. This level is required a new open architecture controller where the external data can be integrated into the tool-path generation process with embedded CAM function inside the controller system.
- The third level is Adaptive STEP-NC programming where the CNC controller estimates online process data and optimizes machining parameters and tool paths in real-time.
- The fourth level is the ultimate goal is Collaborative STEP-NC enabled machining which is to support web-based, distributed, and collaborative manufacturing systems.

The aims are parallel with the e-manufacturing paradigm DA-BA-SA [19,21]: Design-Anywhere, Build-Anywhere, Support-Anyways, where is possible. These aims for collaborative manufacturing providing a digital thread for CNC manufacturing running in the STEP-NC System world via the Internet is achievable. Today's digital communication technologies have solved some critical problems of reliably transferring information across global networks. The STEP-NC is an available interface for exchange information about technology that enabled machining and a new model of data transfer between CAD/CAM systems and CNC machines [22].

2.3 STEP-NC based platforms for robotic machining

The new programming method that uses STEP-NC protocol ISO 10303–238, is increasingly applied in the field of CNC machine tool programming and given that industrial robots are getting more and more capable of taking on machining operations, it is necessary considering to couple the robot for machining towards with STEP-NC protocol [17, 23].
Examples of the applications of STEP-NC standards in programming robots for machining can be found in several research works [23-26].
In paper [23] a computer-aided manufacturing (CAM) system for industrial robot machining operations is introduced. The system is based on the new machining standard STEP-NC which is rapidly making its way into the world of CNC machines. Developed Robot CAM module for industrial robot machining operations based on a STEP-NC input file that can interpret, translate and transfer the manufacturing orders to an industrial robot. The experimental verification was carried out without any material cutting. The generated toolpath was drawn by the robot on millimeter-scale paper.
In research [24] authors proposed the RoboCAD INFELT STEP platform that enables the product designers to program the movement of the robot for a product process plans by means of that product CAD STEP data structure. The RoboCAD INFELT is an interoperable and collaborative platform for CAD/CAPP/CAM applications and integrates the programming data based on ISO 10303 (STEP) standards while supporting the data structures related to robot applications.

The paper [25] represents presented the unified data models of industrial robots under the STEP standard to exchange information between different CAx and robot off-line programming systems. A presented prototype of a robot off-line programming system with a 3D virtual environment (like the function of STEP-NC Machine) will not only benefit the robot simulation systems, but also the improvement of traditional industrial robot controllers. In the developing progress of STEP-CNC, the STEP-NC technology is firstly implemented in a virtual environment. Once the corresponding CAD/CAM and CNC technologies are mature, the STEP-CNC controller will definitely emerge.
The research work [26] proposed a procedure that uses forward and inverse kinematics methods applicable to serial and hybrid robots, allowing STEP-NC compliant information to be received and generates the path along which the robot should move, reducing the time for setup and integration of robots in manufacturing. These paths were tested on three robots with different configurations (AdeptOne, 4-DOF serial robot, ABB IRB-140, 6-DOF serial robot, and Comau Tricept-806, 6-DOF hybrid robot), in a virtual environment, confirming the feasibility of the method.
As above mentioned, STEP-NC promises new opportunities for machine tools and robots programming and according to this, it is useful that high-level object-oriented information in STEP-NC files has to be treated and executed on the machine tool and industrial robot for machining. Levels of research strategies related to STEP-NC presented in section 2.2, could be applicable likewise for programming of industrial robots in machining tasks.
The papers [21,27] is a result of a collaboration between researchers from Brazil and Serbia through a method for applying the ISO 10303-238 (AP-238) standard in robotic machining operations by using two industrial robots (ASEA IRB6-S2 in Brazil and LOLA 50 in Serbia) which use the LinuxCNC control. This collaboration is achievable by using STEP and STEP-NC with aims at providing a digital thread for CNC manufacturing running in the STEP-NC System world via the Internet, thus realizing the paradigm known as e-Manufacturing.

3. METHODOLOGY FOR THE APPLICATION OF PROGRAMMING BASED ON THE STEP-NC PROTOCOL

At the Faculty of Mechanical Engineering, the University of Belgrade, current research in the field of STEP-NC programming based on the ISO10303-238 standard has been going on for more than ten years.

A STEP compliant CNC interface is proposed and developed by the STEP Tools Company [15]. This software, known as STEP-NC Machine, generates ISO 10303-238 files (Application Integrated Model) and works as a front application on a current CNC controller [8]. For our research and application of a new programming method, the licensed software STEP-NC Machine is used.

In this paper, we propose an integrated methodology, as a result of our experiences, for the first level of indirect programming that involves the use of STEP-NC with CNC controllers of machine tools, which are only able to read-only G-code files. Also, this research includes robots for machining that are programmed with either G-code or robotic language, based on their own developed Robot language converters (RLC).

Generated STEP-NC programs that can be shared as data for technology exchange between many organizations and reused on many different CNC machine tools (milling machine, Lathe, Wire EDM, 3D printers, etc.) and robots for machining, where is possible.

One of the common ways to describe the methodology for CNC machining based on STEP-NC is using the IDEF0 diagram [12,17,28,29]. IDEF0 is used to describe a programming method as a structured representation of the activities within the considered programming methodology. This methodology is a structural representation of activity, which can be viewed at several different levels, where each level consists of a set of hierarchical diagrams with text descriptions [17,28].

A special case of one box IDEF0 context diagram, containing the top-level function (A0: Programming method for CNC machining based on STEP-NC) that is modeled with its inputs, controls, outputs, and mechanisms are resented in Fig. 4. Each function or activity in the IDEF0 diagram may be decomposed into its major sub-functions by creating its child diagrams which contain the child boxes and arrows that provide additional details about the parent box.

The basic activities for the programming method for CNC machining based on STEP-NC are:

- A1-Process planning and generating of STEP files, and tool path in CAD/CAM system;
- A2-Machining simulation in CAD/CAM system;
- 4A3-STEP-NC Machine program generator;
- A4-CNC Machining simulation in STEP-NC Machine;
- A5-Web interface for the virtual machine/robots (Digital twin) based on STEP-NC;
- A6-Postprocessing and/or program converter; A7-Virtual machine or robots for machining in the control system;
- A8-CNC machining.

According to the proposed basic flow of activities, shown by the IDEF0 diagram in Fig.4, Process planning and generating of STEP files, and tool path are prepared in the licensed CAD/CAM system (PTC Creo). Results of activity A1 are CAD models of the workpiece, raw piece, tool, fixture in STEP format, as well as toolpath (CLF) for each working step, and are represents an input for activity A2 and activity A3. Activity A2 is used for verification of toolpath and involves simulation of the obtained toolpath, material removal simulation in CAD/CAM environment, with the possibility of simulation by applying configured virtual machine tools, and virtual robots for machining. After that, activity A3, the thus prepared results from previous activities are integrated by loading in the STEP-NC Machine software, where the program is generated in STEP-NC format (*.238, *.p21, *.p28, *.stpnc), according to ISO 10303–238. The advantage of software STEP-NC Machine is that it can combine toolpaths CLF/APT from different CAD/CAM systems (Pro/Engineer, CATIA, UGS NX) and make an integrated program in P21 format, which is of importance if different CAD/CAM environments are used for programming the machining tasks of some complex part [17]. The generated STEP-NC program from activity A3 is an input for activity A4, A5, and A6.

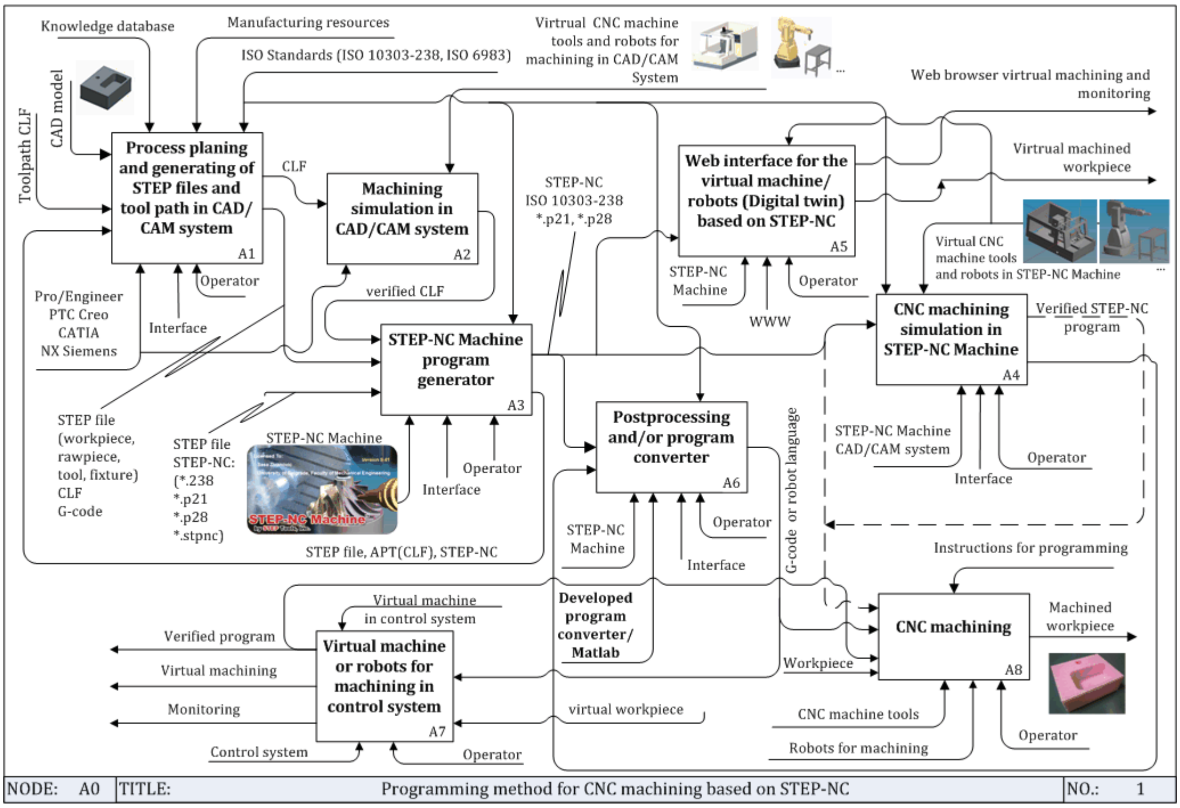

Fig. 4. An integrated methodology for programming method for CNC machining based on STEP-NC

Activity A4 implies performing the Machine simulation based on STEP-NC on available or configured virtual machine tools and virtual robots for machining in order to verify the program. In the era of industry 4.0, activity A5 is especially important, which enables virtual processing and monitoring via the web environment.

Activity A6 is realized as part of software STEP-NC, and with developed program converter, especially for robots for machining. This activity allows post-processing of the STEP-NC program into G-code for machining on the most existing CNC machine tools. Special cases need used developed converter. Activity A7 is optional and is used if the control system has integrated virtual machine tools and virtual robots as a paradigm of the digital twin in Industry 4.0. Finally, in activity A8 is performed program execution and real machining.

3.1 Scenarios for STEP-NC based programming

At the moment, for most users, this new method of programming based on STEP-NC cannot be completely used with all the benefits provided by STEP-NC, because the resources for its development are not available to everyone [28]. This section proposed two possible scenarios (Sc1, Sc2) [13,28,30,31] for indirect programming method based on STEP-NC on existing CNC machine tools and robots for machining using the available and developed software, Fig. 5. These scenarios are:

- Scenario Sc1 - using the native STEP-NC program, post-processing or converting STEP-NC program into G-code and executing on the machine tool or robot for machining which is only able to read-only G-code files.
- Scenario Sc2 - enables the generation of STEP-NC programs based on the available CAD/CAM system and licensed software STEP-NC Machine, in order to exchange technology and machining capabilities on machines that can directly interpret STEP-NC programs, but also those that execute only G-code.

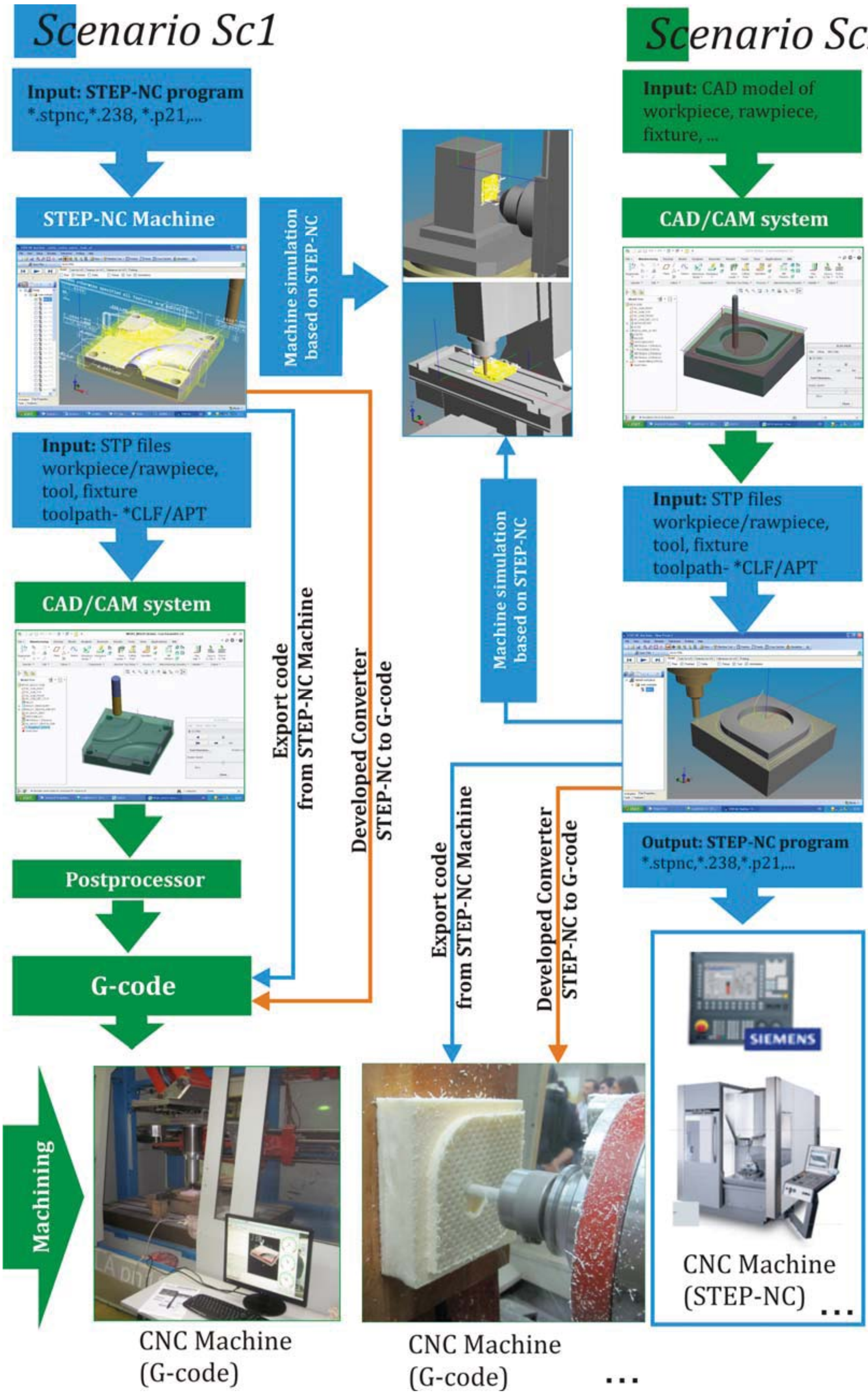

Fig. 5. Scenarios for the application indirect STEP-NC programming method

For now, the first scenario is realistic, for most users, and feasible in three ways. The first way is using CLF, which is specifically imported into the available CAD/CAM system and post-processed for the selected machine tool. CAD system takes reference model and workpiece in STEP format and CL File. Verification of material removal is done in a CAD/CAM system in the module (NC Check). CAD/CAM system uses configured postprocessor to generate G-code for the available CNC machine tools [28]. The second way uses an export code option of STEP-NC Machine which can directly export STEP-NC program into G-code from the available control units, offered by software (Fanuc, Siemens, Okuma, Haas, etc.). The third way is parsing the STEP-NC file and converted into G-code using developed converters.

Scenario Sc2 is primarily intended for the possibility to generate our own STEP-NC program and for the exchange of technology between users to be based on STEP-NC.

Scenario Sc2 involves importing geometry elements of the reference model, workpiece, tool, fixture, measuring probe, and adequate tool path from common CAD/CAM system (Creo, Catia, NX Siemens, ...) into STEP-NC Machine software. The procedure of this scenario can be described through the following steps: (i) CAD models of reference model, workpiece, rawpiece, tool, fixture is prepared in the CAD/CAM system; (ii) technology for machining are planned and implemented; (iii) tool path CLF - Cutter Location File (*.ncl) is generated; (iv) tool path and material removal simulations (NC Check) is done; (v) the inputs for software STEP-NC Machine are prepared by exporting reference model, workpiece and tool from CAD/CAM System in STEP format; (vi) the reference model, model of the workpiece and rawpiece, model of tool in STEP format, and CLF (*.ncl) are loaded in software STEP-NC Machine; (vii) program is saved in the format of STEP-NC AP238 (*.stpnc, *.238, *.p21); (viii) program is tested by simulations on different machines available or configured in the software STEP-NC Machine; (ix) program for machining is directly interpreted on CNC machine which can read STEP-NC programs, or translated into G-code in one of the three described ways in scenario Sc1; (x) workpiece is machined on available CNC machine tools.

These scenarios completely cover the field of application of robots for machining. There are two possibilities of preparing programs that can be either in the format of G-code or robot programming language (using developed RLC [17]).

4. CONFIGURING OF VIRTUAL MACHINE TOOLS AND ROBOTS IN STEP-NC ENVIRONEMNT

STEP-NC Machine can display and simulate the machining or measuring process within a STEP-NC file, including the simulation of virtual machine tool, or virtual robots, or virtual measuring machine and it can be extended as needed to simulate new machines. Thus, the STEP-NC Machine environment allows configuring its own virtual CNC machine tools and virtual robots for machining. In this way, it is possible to perform a simulation based on the generated STEP-NC programs in order to verify them.

Virtual CNC machine tool or robot for machining is able to interpret the STEP-NC program in the software STEP-NC Machine environment. To load the new machine in the STEP-NC environment, it is necessary to follow the next procedure: (i) configuring a CAD model of the CNC machine tool or robot for machining; (ii) make an export model of the CNC machine tool or robot for machining in the STEP format by the protocol AP203, AP214 or AP224; (iii) configuring virtual machine or robot in STEP-NC Machine environment; (iv) prepare XML file which includes characteristics of a machine tool or robot; (v) include both files for the machine (STEP file and XML file) in folder machine in software STEP-NC Machine; (vi) start STEP-NC Machine and in the Machine tool drop-down menu it will appear the new configured machine tool or robot ready for Virtual machining, based on STEP-NC program [32].

In the process of configuring a virtual machine, a description of the structure defined by the XML file is very important. The characteristic structure of the XML file for machine tools or robots for machining is given in Fig. 6. This figure shows fragments of XML files for one Horizontal machining center LOLA HMC500, and for one robot for machining LOLA 50.

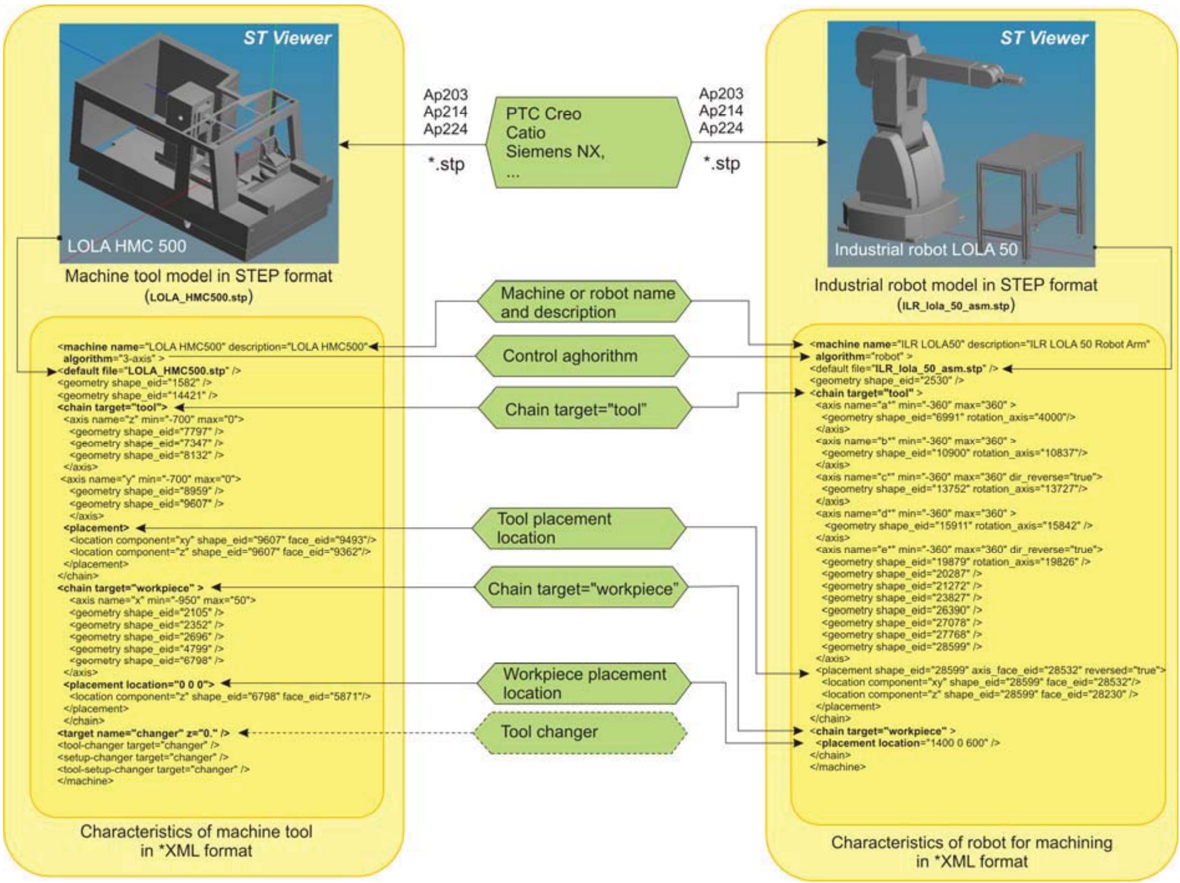

Fig. 6. Configuring virtual machine and robots for machining in STEP-NC Machine environment [32]

The usual XML file structure for description structure of machine tools and robots for machining has the following parts [32]: (i) machine or robot name, (ii) control algorithm, (iii) name of the STEP file of machine or robot, (iv) description of the machine or robot base structure, which is stationary, (v) description of tool side structure, (vi) defining placement location for tool, (vii) description of workpiece side structure, (viii) defining placement location for workpiece, (ix) description of NC axes and their feeds, or description rotating joints of robots (name a, b, c, d and e, constraints, mutual position, as well as the sequence of rotary axes). Thus, the configured own virtual machine tool and robot for machining can be loaded in the STEP-NC Machine environment, where they will appear as new machines in a dropdown menu of Machine Tool. Upon selecting the machine from the menu, it is loaded and can execute STEP-NC programs. This is important for training in a new method of programming because it is now possible to check STEP-NC programs by simulating work on own configured virtual machines or robots for machining.

4.1Configured virtual machine tools

The configured types of CNC machine tools so far are shown in Fig. 7. The available machines for which the first level of indirect programming based on STEP-NC was applied were considered.

The types of machines considered in Fig. 7 are: (i) CNC machine tools - (1-5) for milling operations with serial kinematics (3 to 5 axis), PKM (Parallel kinematic machines) - (6) Hybrid Kinematic Machines - (7); (ii) CNC lathe for turning operations – (8,9); (iii) Wire EDM for electrical discharge machining – (10); (iv) 3D printers, for additive manufacturing – (11,12); (v) CMM (Coordinate Measuring Machine) for measuring – (13).

A more detailed procedure for configuring new machine tools in STEP-NC machine is given in [33], and some results also can be seen in

[13,32,34-36]. The existing database of available machines in the STEP-NC machine software has been significantly upgraded with new machines.

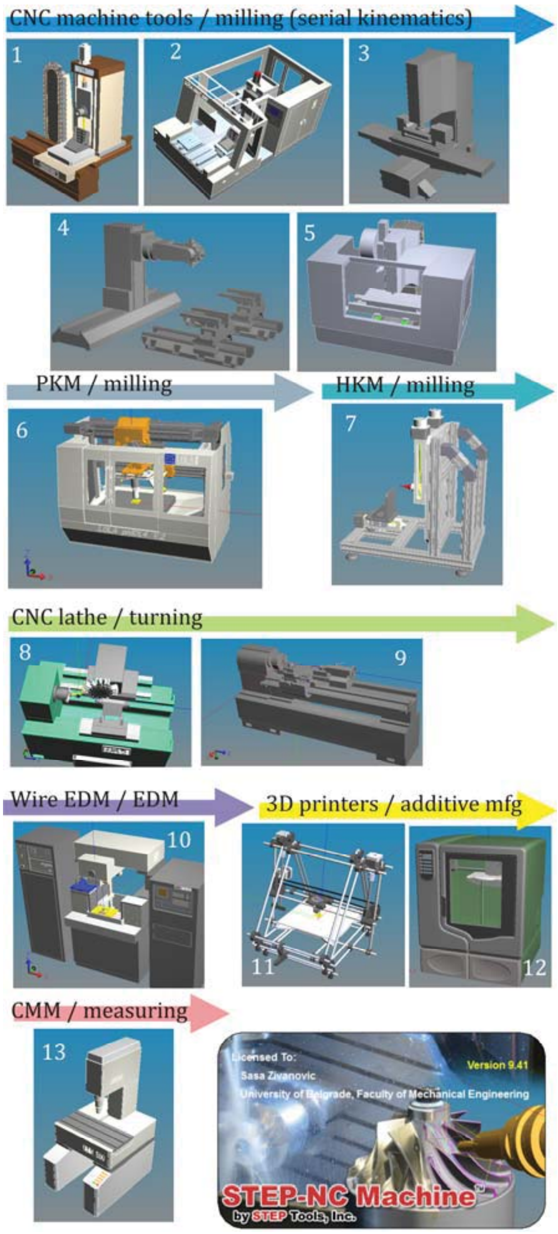

Fig. 7. Example of configured machine tools in STEP-NC Machine

4.2 Configured virtual robots

Used own methodology for configuring robot is described in more detail in [16,37,38]. So far, a number of robots have been configured, such as: LOLA, Mitsubishi, Fanuc, Asea, ABB robots. Some of the configured robots are shown in Fig.8.

Fig. 8. Example of configured virtual robots for machined in STEP-NC Machine

In Fig. 8 the following robots are shown: (1) - ASEA Irb-S2, (2) - Gosko, (3) - LOLA50, (4) - LOLA15, (5) - Mitsubishi rv6s1, (6) - Mitsubishi Movemaster EX, (7) - ABB irb140, (8) - Fanuc LR Mate 200iD.

As already shown, an example of the XML files description for the 5-axis machining robot LOLA50, with comments and illustrations are given in Fig. 6-right. In order to correctly create the XML file structure and the description of the assembly components, the robot model in STEP format is loaded in the software ST Viewer which is used to define geometry shape_eid for each part and face_eid for corresponding surfaces. Three elementary entities can be distinguished in a structure: robot stationary components (base, working table), chain target tool, and chain target workpiece. All movable rotational joints are placed here on the side of the tool. For each axis, the elements that have to be defined are: name (a, b, c, d, e), constraints, mutual position, as well as the sequence of rotary axes. The placement location for the workpiece is defined with respect to a specified coordinate system of the robot (robot zero-configuration).

Configured machine tools and robots can also be used in a WEB interface which is shown in more detail in the next chapter.

4.3 Web interface for the virtual machine tools and robots for machining

A configured virtual machines and robots in a STEP-NC Machine environment can through a Web interface and local server enable accessibility on a cloud platform for simulation and monitoring.

Web interface based on STEP-NC is used NC.js. The NC.js package is implemented in JavaScript. The web interface on the local server can use the STEP Tools Machine commercial software [15] which can display the 3D models for the machining workpiece, tools, measuring probes, CNC, robots for machining, or CMM as well as material removal simulation, measuring path simulation, etc.

Procedures for build and run server can be viewed at [39]. The NC.js package is built from the source using the Node Package Manager. This will assemble all of the dependencies, including a pre-built version of the STEPNode plugin, and then start the server on a STEP-NC file that you specify. First, it needs to install Node, and after it is installed, it is necessary to download the NC.js source code from GitHub. In the top-level directory of the NC.js package, the file "config.js" and the STEP-NC file can be edit, as also the machine tool model sample which is used in the STEP-NC Machine desktop software package. After successfully install Node and NC.js packages, a build and run server is available. When the server is running, start the web browser to address http://localhost:8080/, and you will see a machining setup shown in Fig.9 and Fig.10. After virtual machining, it is possible to download the virtual machined part as an STL file, for further qualitative analysis.

Two examples of virtual horizontal machining center LOLA HMC500, and industrial robot Gosko in WEB environment, where execute STEP-NC program and doing virtual machining, are shown on Figs. 9 and 10.

Web interface and local server can enable accessibility on a cloud platform STEP-NC environment for simulation and monitoring using a laptop computer, tablets, Smart Phones, and other mobile devices on any type of web browser (Fig.9 d, e, f).

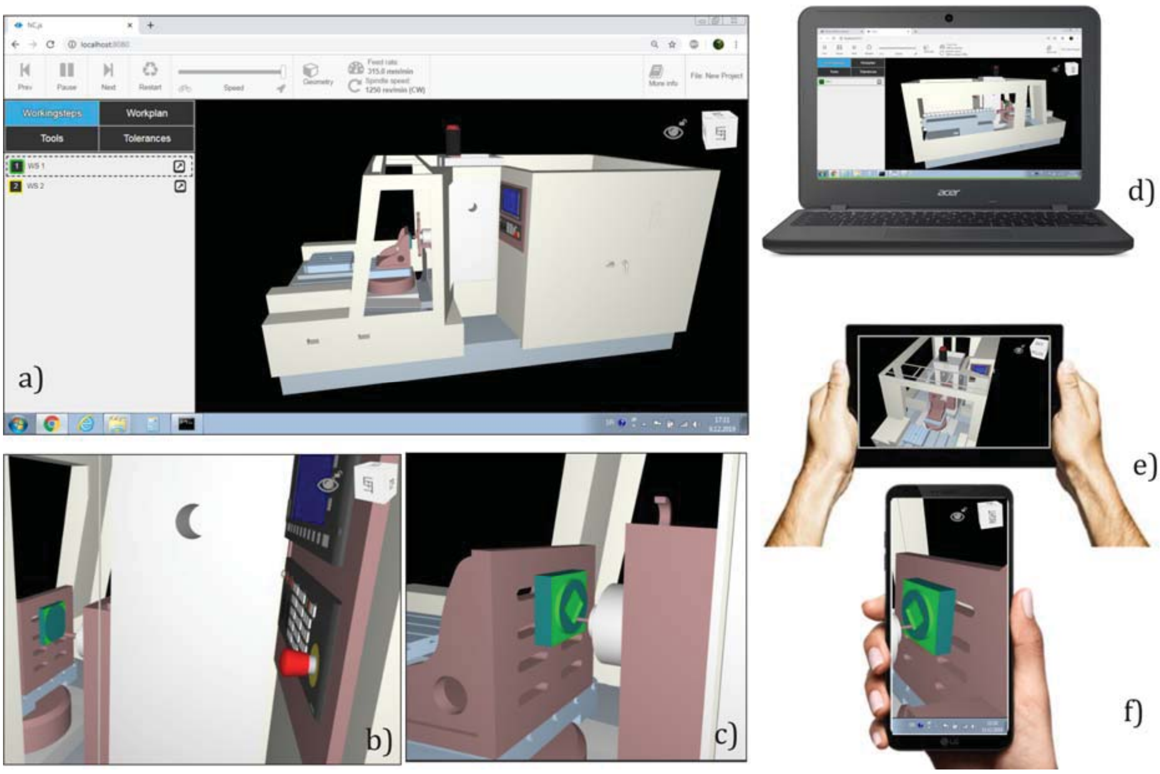

Fig. 9. Examples of configured machine tool in a WEB interface on local server

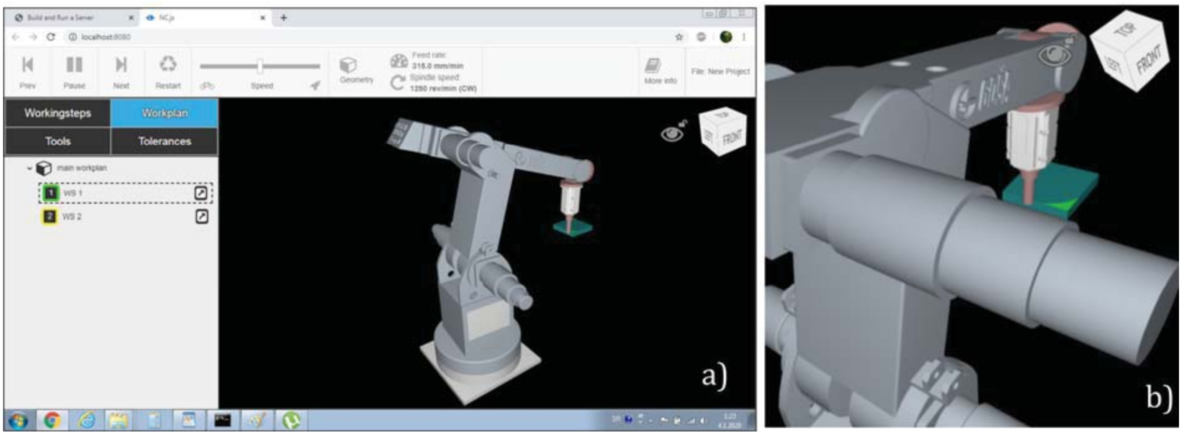

Fig. 10. Examples of configured virtual robot in a WEB interface on local server

In this way, it is possible to create interactive websites to share machining programs to get feedback. This is an example of the application of STEP-NC in the era of Industry 4.0 through Collaborative manufacturing, which would include here connect product design, manufacturing, and inspection with a digital twin, built-in real-time while machining with a new 3D model-based simulator [15,39].

5. PROGRAMMING ROBOT FOR MACHINING BASED ON STEP-NC

It can be said there are not many researches works on the application of STEP-NC in generating programs for industrial robots for machining. One of the reasons for the difficulty in applying STEP-NC to robots is that the controller needs to receive commands in a specific language imposed by each manufacturer, resulting in a large number of robot programming languages and difficulty in achieving standardization [26].
The focus of our research work is to contribute to the implementation of STEP-NC in the generation of native programs for industrial robots, without making changes in the robot control system [17].
The application of such a programming method does not involve additional costs and aids the integration of currently active industrial robots with the STEP-NC standard, which can be extended very easily to the existing robot controller even though it cannot currently benefit from all the innovations of STEP-NC [17].

Nowadays programming of industrial robots in machining tasks can be done in several ways [17,38]: (i) using CAD/CAM systems for programming of the multi-axis machine tool with the use of appropriate converters of CAM data (Cutter Location File – CLF and G-code) in native robot language, (ii) by postprocessing CLF, from current CAD/CAM systems for multi-axis machining to G- code if the robot controller can directly interpret G-code, and (iii) using specialized CAM software for programming of robot for machining that generates directly native robot language using appropriate postprocessors for robots, Fig.11.

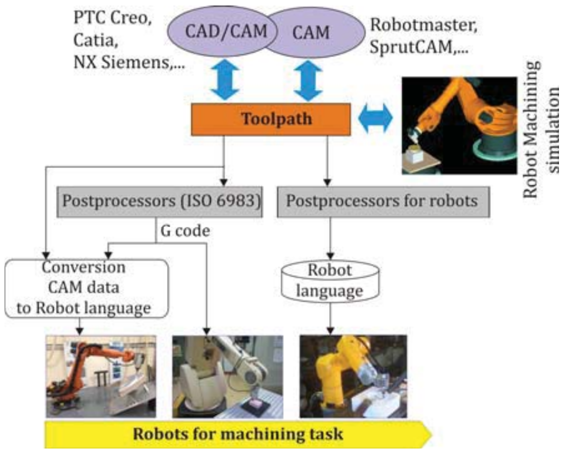

Fig. 11. G-code or robot language manufacturing data chain [17]

As already stated, the STEP-NC provides bi-directional data flow between CAD/CAM and CNC machine tools or robots for machining without losing information if they can directly interpret the STEP-NC program, i.e., if they have

a control unit that supports a new method of programming. There are practically no such commercial robots.
As it is presented in Fig.12, this research topic is to indirectly use the STEP-NC program on robots for machining. This can be done in two ways: (i) using the export option in STEP-NC software to export the program into G-code if the robot controller can directly interpret G-code, or (ii) by using appropriate converter in order to translate the STEP-NC program into a native robot language [17].

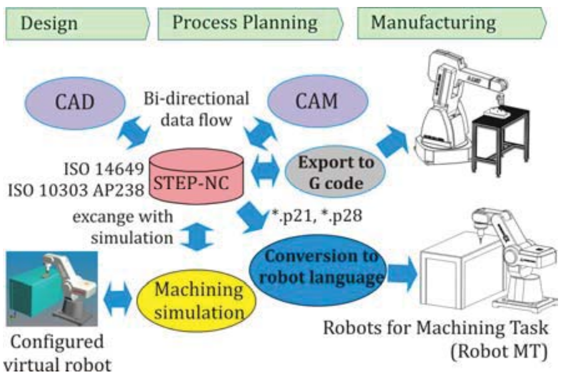

Fig. 12. G-code or robot language manufacturing data chain based on STEP-NC [17]

The developed programming method is applicable directly by CNC machine tool programmers by using the existing available CAD/CAM systems. Also, the methodology includes the developed procedure of configuring and integrating virtual robots for program simulation and verification. In order to realize real machining tasks, and considering that there are no robot controllers that can integrate STEP-NC programs directly, the methodology employs an indirect STEP-NC programming method to translate the program based on the ISO 10303–238 standard, using a developed converter for the STEP-NC program translation to robotic programming language [17].
Programming robots for machining based on STEP-NC is used to create machining programs that can be shared between many organizations and reused on many different machines and robots. With STEP-NC Machine, the execution of a STEP-NC program can be directly simulated on the configured virtual robots for machining, to make sure it will execute correctly using adequate modeled tools and fixtures. Also, in this way is a possible directly interpreted STEP-NC program on available or configured virtual robots which is an integrated part of the software. This option is important for the purpose of verifying programmed tool paths, as well as for training and education.

6. DEVELOPED CONVERTORS FOR MACHINE TOOLS AND ROBOTS FOR MACHINING

Our research presented in paper [16,17,38] considers an Indirect programming method, based on standard ISO 10303–238, using the developed Robo STEP-NC converter i.e. Robot language converter (RLC), Fig. 13, which is employed for translating the exported STEP-NC *.p21 file into robot programming language in two ways: (i) G-code, or (ii) robot programming language.
This converter can be used for both industrial robots and machine tools with appropriate customization of the program output format, Fig.13.

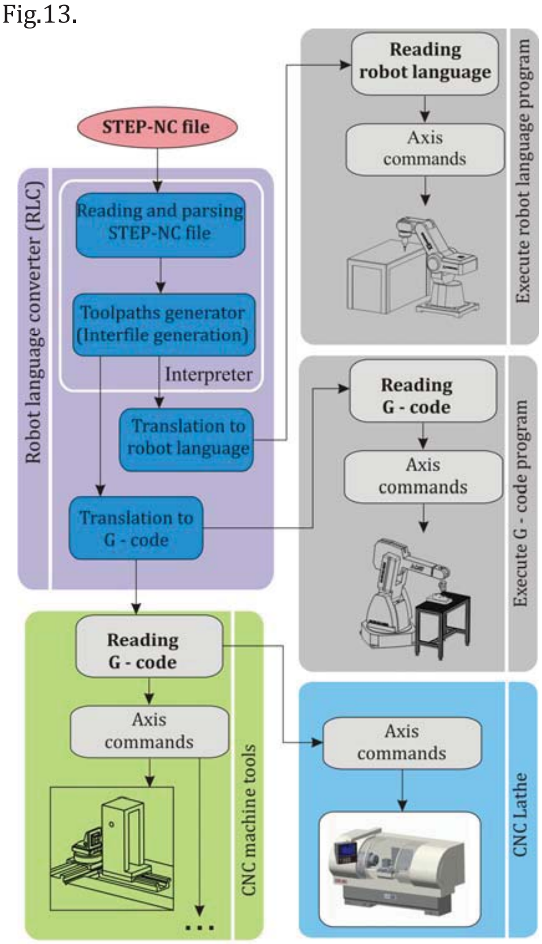

Fig. 13. Indirect STEP-NC programming method for machine tools and industrial robot for machining

The complete procedure of STEP-NC program conversion to G -code or robot language can be seen in [16,17]. This procedure should involve a STEP-NC program interpreter and its translation into an appropriate language. Main activities during translation STEP-NC program are: (i) reading and parsing P21 file, (ii) toolpath generator (Interfile generation), (iii) translation to G-code or robot language, (iv) toolpath simulation of generated G-code or robot language, and (v) execution of program on the real robot or CNC machine tool.
During further research, it is planned further development of the converter for different robot languages and specific G-codes.

7. DIGITAL THREAD FOR MANUFACTURING CAD-CAM-STEP-NC-CNC

The digital thread for manufacturing refers to the communication framework between CAD-CAM-STEP-NC-CNC that allows a connected data flow and integrated view of the product data throughout its lifecycle [40].
Primary trends of digitalization in the manufacturing industry are increasing efficiency, productivity, and the quality of products. As a base of the modern manufacturing industry, CNC machine tools and industrial robots play an essential role in industrial digitalization in the era of Industry 4.0 [3].
In this regard, the key link that forms the digital thread is STEP-NC as the interface between CAD/CAM and CNC. Nowadays, when the development of complex products involves the participation of different teams working in different environments, it is necessary to have an environment that can connect this work into an efficient integrated whole for the needs of manufacturing that product. For example, STEP-NC Machine can combine toolpaths APT/CLF from different CAD/CAM systems (Pro/Engineer, CATIA, UGS NX), Fig. 14, and form an integrated program in format P21, which is of importance if different CAD/CAM environments are used for programming the machining of some complex part.
On the other hand, the integrated technology thus obtained can be converted into the desired output, Fig.14, according to the available resources of the machine tool or the robot for machining. Desired output is possible using the export code option of STEP-NC Machine (Fanuc, Siemens, Okuma, Haas, Heidenhain, ..., APT, ...) or using developed converters.

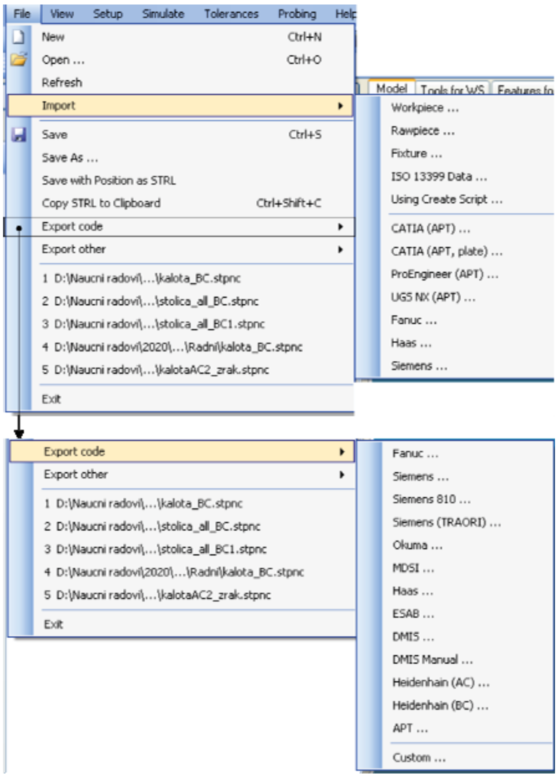

Fig. 14. Import and Export STEP-NC interfaces

Figure 15 shows an integrated digital thread for manufacturing based on STEP-NC. This is a demonstration of research at the Faculty of Mechanical Engineering in Belgrade, which is prepared in a similar way as demonstrations which organized STEP Tools [15] in order to promote this method of programming.
This figure shows mainly the application of STEP-NC programming methods on available machines and robots at the Faculty of Mechanical Engineering University of Belgrade, and the results of cooperation with the Faculty of Technical Science University of Novi Sad [13,41,423], Faculty of Mechanical Engineering University of Banja Luka [13], and the Mechanic and Mechatronic Engineering Department, University of Brasilia [21,27].
The Fig. 15 shows all the elements of the digital thread for manufacturing based on the STEP-NC Machine software and the ISO 10303-238 standard as data flow and integrated view of the product data throughout its lifecycle, both in virtual and real world.

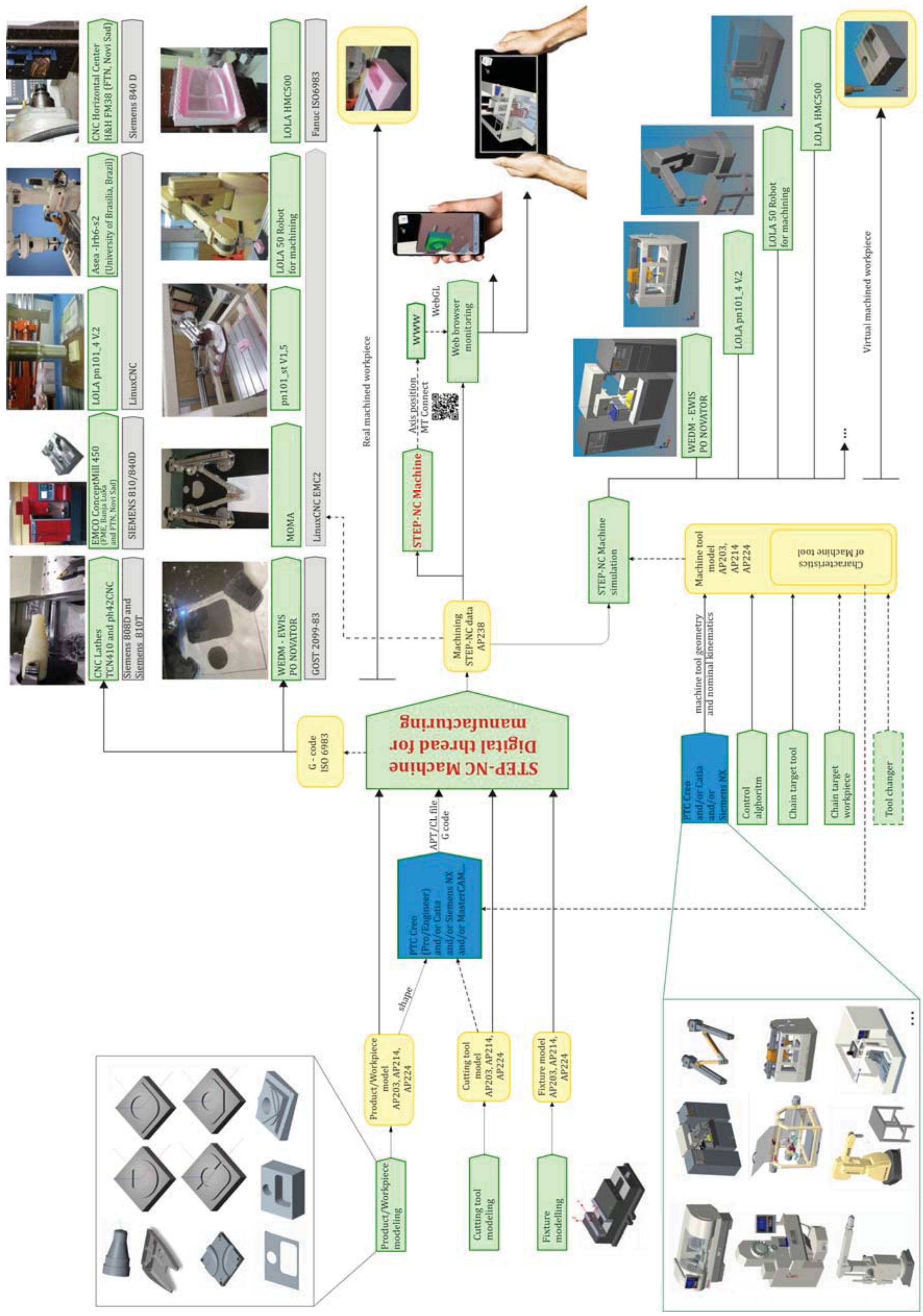

Fig. 15. Digital thread for manufacturing based on STEP-NC

8. EXPERIMENTAL VERIFICATION OF STEP-NC PROGRAMING IN ACTUAL PRODUCTION CONDITIONS

The aim of machining experiments is to test the methodology for the application of programming based on STEP-NC standards, for configured CNC machine tools and robots for machining. CAD/CAM system PTC Creo and STEP-NC Machine software are used to prepare the program and models of virtual machines or robots. After the simulation process is completed, the postprocessing or converting of STEP-NC programs in G-code or robot language follows.

In mostly where the available machines and robots cannot directly interpret STEP-NC, two approaches can be applied: (i) choosing an internal application for direct export of STEP-NC program to G-code in the STEP-NC Machine software, Fig.14, (ii) using developed converters for specific G-code format, or robot programming language.

Verification of the programming method and virtual machining workpieces using the STEP-NC is realized through several machining experiments.

8.1 Benchmark test

The first experimental verification was realized by processing a benchmark workpiece based on the original STEP-NC program according to ISO 14649-11 (ARM model). There are five machining working steps in the original file: milling the top surface of the workpiece; drilling and reaming the hole; and rough and finish milling the pocket.

NIST has built two STEP-NC interpreters [15,43] for milling operations, one using STEP-NC AIM (ISO10303-AP238), and the other using STEP-NC ARM (ISO14649-10-11). The system outputs Canonical Machining Commands (CMCs) [43,44].

Original STEP-NC program according to ISO 14649-11 is translated using STEP-NC interpreter [15] in Canonical Machining Commands (CMCs), and then these CMCs are translated into G-code. Machining was realized on a vertical 3-axis machine with parallel kinematics LOLA pn101_4 V2, Fig.16a. The scaled benchmark workpiece was also machined on the desktop variant of the vertical 3-axis machine with parallel kinematics pn101_st V1.5 [45], Fig.16b.

In the following, we used the proposed methodology to generate a STEP-NC file for this benchmark test, but according to the ISO 10303-238 standard (AIM model), while the tool path was achieved using a developed converter to the appropriate G-code. Figure 16c shows the machining of a benchmark workpiece on a robot for machining LOLA 50 [16], which is programmed in G-code [46]. G-code is obtained using a developed Robo STEP-NC converter.

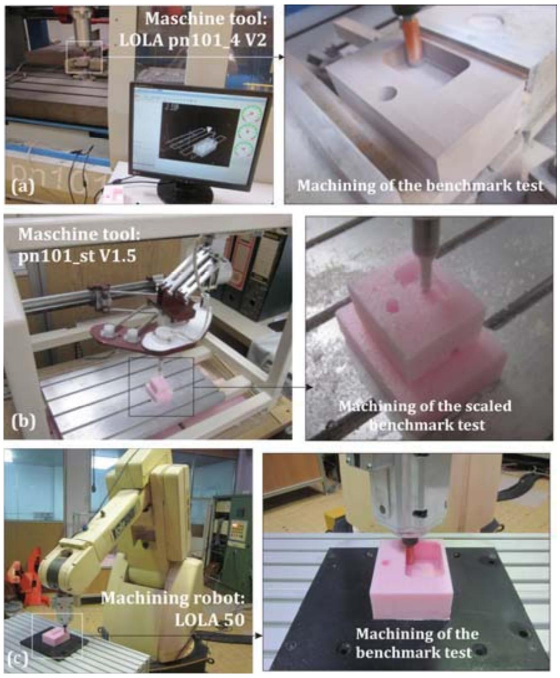

Fig. 16. Examples of machining 3D benchmark test

We also provide examples that refer to the machining 2D benchmark workpiece based on the STEP-NC program according to ISO 10303 AP238, Fig.17, for the 2 axis Wire EDM machine [35], and reconfigurable 2-axis parallel kinematic machine MOMA [47].

For preparing all inputs for generating STEP-NC file, used CAD/CAM system PTC Creo, were also performed tool path verification, Fig.17a. A generated STEP-NC file in P21 format and an example of its tool path simulation in STEP-NC Machine is shown in Figure 17b.

The 2D benchmark workpiece has 3 machining features: two inner contours of the circle and a rectangle with rounded edges and an outer contour of a rectangle shape [32]. The contour of the workpiece was cut in aluminum sheet with 2 mm thickness on WEDM machine Ewis. This 2D benchmark workpiece contours on the second 2-axis reconfigurable parallel kinematic machine (MOMA) were plotted on the paper, Fig.17c.

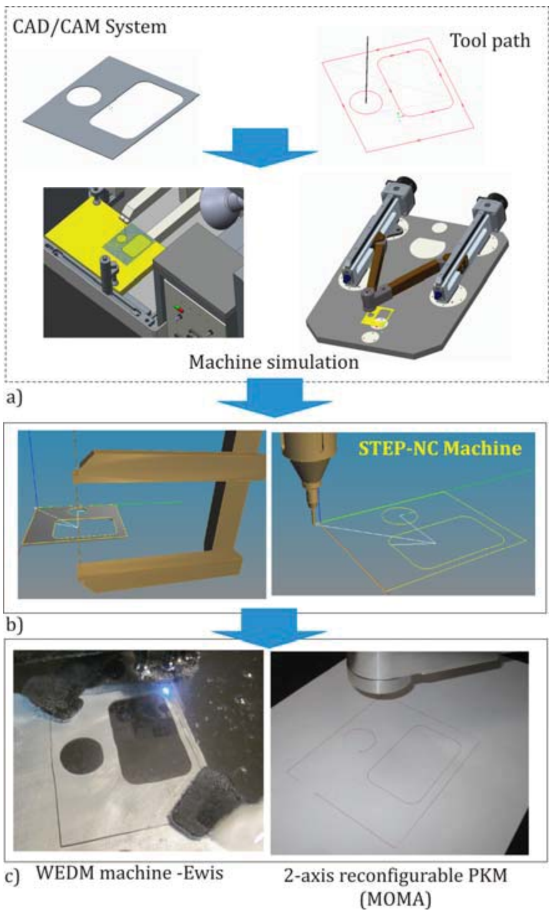

Fig. 17. Examples of machining 2D benchmark test

8.2 Mill machining experiments

For a group of experiments related to the machining of original STEP-NC files from STEP Tools [15], machining of parts Fishhead, NAS979, and Moldy part was performed.
The first example is Fishhead, and for this example is used scenario Sc1, where the original STEP-NC program (AIM model) is translated into the G-code and then it was machined on three different machines, with three different control system: (i) LOLA HMC 500, Fanuc (FME-BG), (ii) 3 axis vertical milling machine with parallel kinematics LOLA pn101_4 V2, LinuxCNC (FME-BG), and (iii) CNC Horizontal center, H&H FM38 Siemens 840D (FTN-NS), Fig. 18.

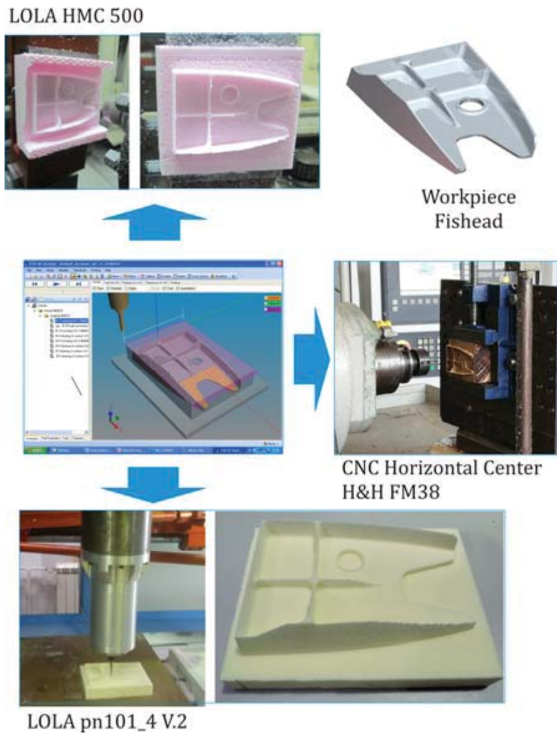

Fig. 18. Examples of mill machining based on STEP-NC

Example of machining test workpiece NAS 979 (circle/diamond/square test) according to the scenario Sc1, use original STEP-NC program translated into the G-code and then it is machined on the 3-axis vertical milling machine with parallel kinematics LOLA pn101_4 V2, Fig.19a.

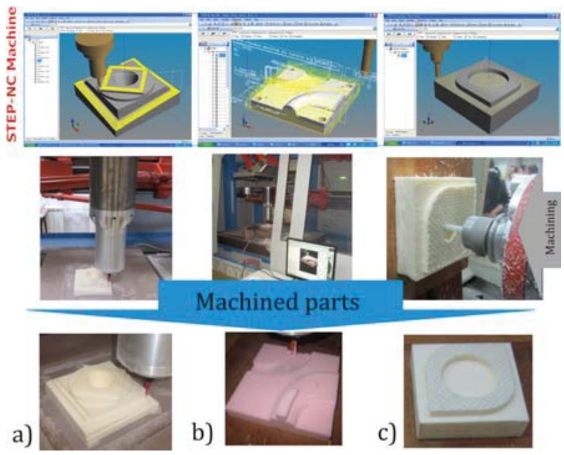

Fig. 19. Examples of mill machining

Previously necessary simulations were made (in STEP-NC Machine) for the reconstruction of

machining technology for a test workpiece NAS 979. File format STEP-NC for part NAS979 is directly translated into Fanuc G-code using the Export option of software STEP-NC Machine [2]. As a part of the promotion activities on the STEP-NC [48], the test workpiece NAS979 is machined during a presentation in Orlando (Florida, USA, 2005.) [49].
The machined part in Fig.19b is the Moldy part which is also the original STEP-NC program translated into the G-code and then it was machined on the 3-axis vertical milling machine with parallel kinematics LOLA pn101_4 V2. Moldy mold test part was used on demonstration the STEP Manufacturing team met in Renton, Washington to demonstrate and discuss advanced use of the STEP-NC AP238 standard. The key goals for this round of demonstrations were to have multiple sites machine the same part from the same AP-238 data, and to show AP-238 can be used for molds [50].
To verify the Sc2 scenario, a set of parts was prepared, one of which as an example of machining is shown in Fig. 19c. Scenario Sc2 enables importing geometry elements of the reference model (Fig.5), workpiece, tool, and tool path from common CAD/CAM system into STEP-NC Machine software where STEP-NC file is generated in P21 format. After that is used option export to G-code for Fanuc CNC control, and machining result on horizontal machining center LOLA HMC500 is shown in Fig. 19c.

8.3 Machining experiments on lathe

Verification of the developed programming methodology using STEP-NC protocol, through machining of parts on available CNC lathes was performed in the laboratory with programming, simulation, and translation of the STEP-NC program in format P21 into G-code [51,52].
The software STEP-NC Machine was used to generate the STEP-NC program in P21 format where the simulation was performed on the configured virtual CNC lathes. After that, the translation of the STEP-NC program into G-code was performed.
Figure 20 shows an example related to the complete machining of a workpiece (including roughing and finishing) on a TCN410 CNC lathe, based on STEP-NC protocol.

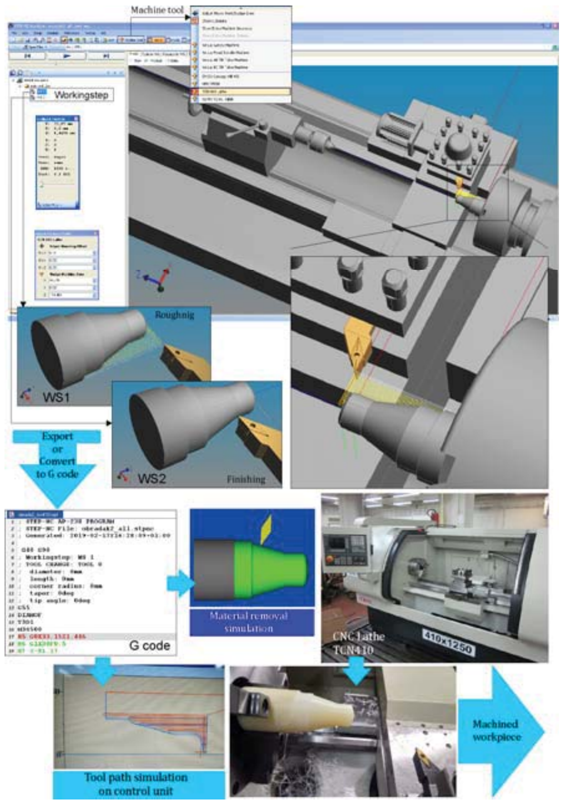

Fig. 20. Example of machining on CNC lathe

During the machining on the CNC lathe, two working steps were performed: roughing and finishing. After generating the STEP-NC program in P21 format and simulating on the TCN410 virtual lathe in the STEP-NC Machine software, the program was translated to G-code for the Siemens control unit. The program obtained in this way in the G-code was additionally tested in the CIMCO program environment, as well as on the control unit of the Siemens Sinumerik 808D, after which the workpiece on the machine was machined.
By machining the selected trial part, the possibility of applying a new programming method based on the STEP-NC protocol was confirmed, using a hybrid programming method which at this stage is reduced to translating the STEP-NC program to G-code using the Export option of STEP-NC Machine software or using developed converters for the specific format of G - code.

8.4 Robot machining experiments

The first results in the application of the indirect programming method based on the

STEP-NC standard ISO 10303-238, applicable on robots for machining were achieved on the LOLA 50 robot [16], and then on the Mitsubishi Movemaster EX robot [17].

The first example, presented here, refers to the machining of a typical STEP-NC benchmark project, which already shown in Fig. 16c. Although this example is provided in ISO14649-11, in this example it has been remodeled according to ISO10303-238, because the proposed programming methodology for robots includes software STEP-NC Machine, which cannot read the P21 file according to standard ISO 14649. For this example, we prepared a CAD model in STEP format for the workpiece, tool (diameter 12 mm), and tool path in APT/CLF. There are three machining working steps. They are for milling the top surface of the workpiece, drilling, and milling of the pocket (rough and finish).

By applying the proposed methodology from Section 3, models of the workpiece, tool, and toolpath were loaded in software STEP-NC Machine, and STEP-NC file was generated in format P21. For the thus obtained program, the configured virtual robots are available for machining simulation according to this program. After successful machining simulations, the obtained P21 file was translated, using the developed module RoboSTEP-NC [16], whereby G-code is obtained and adapted to direct application on available 5-axis machining robot LOLA50.

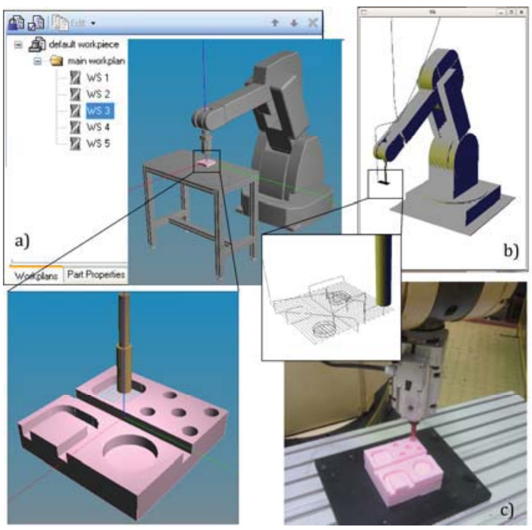

Fig. 20. Example of machining on robot LOLA50

The second example refers to the machining of a specially designed test workpiece, which includes trajectory milling, pocket milling, and drilling. The procedure of program preparation and verification is identical to the one presented for the first example. Simulation results in the STEP-NC Machine software for the program in P21 format are shown in Fig. 20a. The robot control and programming system are based on the LinuxCNC for which a virtual robot was also developed to meet the needs of off-line machining simulation [53]. The G-code obtained by applying the developed module RoboSTEP-NC [17] is verified once again, on a virtual robot integrated with the control system, Fig.20b, and thereafter the machining of a workpiece is executed on the robot, Fig. 20c.

The third example refers to experiments on the 5-axis robot Mitsubishi Movemaster EX was to verify the proposed methodology for indirect programming that includes: generating the program in P21 format, machining simulation on a configured virtual robot (Fig.21a,c), and translating STEP-NC *.p21 file to native robot language by applying the, developed converter [17].

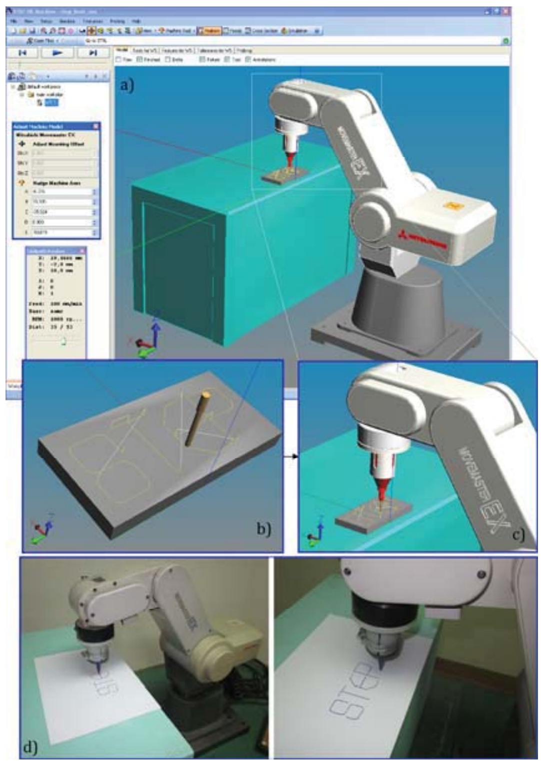

Fig. 21. Example of contour drawing on Mitsubishi Movemaster EX robot

Verification of this indirect method for robot programming using the STEP-NC is realized through drawing contours. The presented example, Fig.21b, refers to the programming of drawn contours, which includes linear and circular segments. This contour is a specially designed word "STEP". The drawing of this contour on a robot is shown in Fig.20d.

STEP-NC based machining architecture applied to industrial robots is a topic of cooperation between the Faculty of Mechanical Engineering University of Belgrade and the Mechanic and Mechatronic Engineering Department, University of Brasilia. DA-BA-SA concept of collaboration between researchers from Brazil and Serbia [21,27] through method for applying the ISO 10303-238 in robotic machining is shown in Fig.22a. The method encompasses programming based on STEP-NC, simulation, and machining by industrial robots in Serbia and in Brazil. Application and validation of robotized machining are performed using two industrial robots (ASEA IRB6-S2 and LOLA 50) using the LinuxCNC control system, Fig.22b.

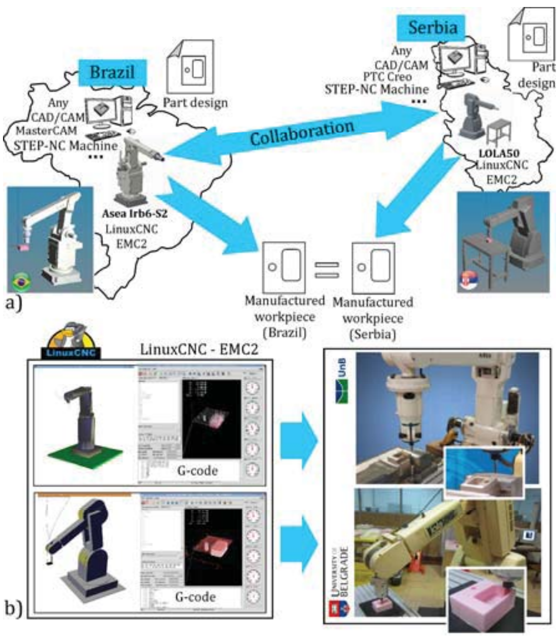

Fig.22. E-manufacturing context using STEP-NC

Initially, a 3D part is designed using any CAD system, and it is sent through the Internet to a CAM specialist who uses an adequate available software to generate a process plan in a STEP-NC format. Then, machine operators in Brazil or Serbia download the part design and its process plan in a STEP-NC format and simulate machining based on working steps data. Finally, machining with real robots in Brazil and in Serbia is carried out [21]. The ISO 10303-238 is the first step toward smart manufacturing and concept for Industry 4.0 which allows cloud manufacturing possibility, which is demonstrated through this collaboration.

9. CONCLUSION

In order to contribute to efficient applications of a new method of programming based on STEP-NC protocol (ISO10303-238), the focus of our current research is related to applying STEP-NC, for programming different kinds of CNC machine tools, as well as a robots for machining. This paper presents the results of ten years of research in this field, which does not lose its relevance. Through developed methodology and experimental validation through machining based on STEP-NC, our research and collaboration are presented.

STEP-NC (ISO10303-238) is an object-oriented standard that is well adapted for exchanging high-level manufacturing data. It provides a new vision of the numerical chain with multidirectional exchange possibilities. For now, the application of STEP-NC-based programming methods is limited and is applied mainly at the first indirect level that applies to machines that can only execute G-code. It can be said that companies cannot get rid of their existing CNC controller and CAD/CAM solutions, so the implementation of STEP-NC has to be achieved step by step. In order to fully realize the STEP-NC concept, the development of a STEP-NC compliant controller is crucial.

A new vision of CAD/CAM/CNC data chain, with STEP-NC as the interface, has large benefits for the manufacturing industry in terms of efficiency and interoperability. The applying STEP-NC protocol is also compliant with the developments of Industry 4.0, concepts of digitalization such as virtual machine tools and robots as a paradigm known as a digital twin, cyber-physical systems, and cloud computing.

The suggestion of future works includes the further development of converters for specific G-code and new robotic language, as well as the transition to the second level of direct interpreted STEP-NC programming where axis command is directly executed from STEP-NC file.

Acknowledgement

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