Modular Approach in CNC Kernel Development

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***Abstract*—Most small design bureaus have to order prototypes from third-party organizations which elongates development time. A possible solution to the problem may be using modular equipment which reduces the cost of obtaining the required machines and development time. However, such equipment needs a computer numerical control system that could quickly adapt to hardware requirements. An approach to control system design is proposed that implies the development of numerical control kernel from independent modules interacting via a unified programming interface with a high level of granularity which will allow rapid development of a required configuration. The possibility to use existing open control systems as a basis is also considered in the paper, which can minimize the design time. The solution is based on a multiprotocol control system and provides the possibility to combine software and hardware components from different manufacturers. A motion planning module was developed based on the proposed approach which can be embedded in an open system Smoothieware and expand the its capabilities in terms of trajectory complexity and quality of obtained surface. Simulations of the motion planner performance were carried out for linear and complex trajectories and showed minimal contouring and linear errors. The work is aimed at increasing the economic independence and competitiveness of small design organizations and enterprises. The proposed modular approach allows obtaining the required equipment and its control system with minimal design time which can significantly expand the capabilities of rapid prototyping and ensure the prompt production of pilot batches.**

I. Introduction

Among the main problems faced by small organizations and design bureaus, also called start-ups, that do not have their own manufacturing premises is the development of prototypes and pilot batches.

These organizations are most often forced to use services of third-party manufacturers [1]. However, this decision leads to an increase in time and cost of production. Since the distinguishing feature of these design bureaus is the development of innovative products with the minimal design and launch time, the success of the project relies greatly on the speed of prototype development and tests.

Another possible solution to this problem for an organization is to purchase the required equipment and create its own production site. This decision also has a number of disadvantages. Firstly, due to current trends in the field of instrumentation, as well as the wide introduction of the Industrial Internet of Things, most of products have complex geometry, as well as electronic and electric components. Development of this type of products requires the use of a wide number of expensive specialized equipment, purchasing which may be unprofitable or even financially unavailable for a small organization. This decision is also considered impractical due to rapidly changing nomenclature.

The optimal solution may be in the use of modular equipment, which allows obtaining the required type of a machine tool by replacing individual physical components i.e. modules. It makes it possible to get the equipment needed for a specific project. This way, a small enterprise can achieve the required level of economic independence and produce prototypes in a short period of time without the involvement of third-party organizations and with minimum costs.

It should be noted that, since modular equipment provides the possibility of various types of processing, a numerical control system (CNC) suitable for each type of machine tool is required for its successful operation. Therefore, the problem of obtaining CNC systems for each type of required processing arises. Possible solutions include the following:

- The use of specialized commercial CNC systems.
- Development of a CNC system from scratch.
- The use of CNC systems with open source code.

Purchasing a commercial CNC system, despite its obvious advantages like high processing speed and precision, can be considered inexpedient. Most of CNC systems are designed either for one type of processing or for a small variety most often consisting of milling, laser cutting and turning [2]–[4]. And since the modular equipment capabilities include a much wider selection of possible machine tools, it requires the purchase of multiple systems to control each of these units. This, together with the high cost of specialized CNC software, makes this solution impractical.

Another solution may include the development of control systems for each type of processing individually. However, this will significantly increase the development time. Therefore, the main approach in this case is universality, which is applied in the proposed solution.

Finally, it is possible to introduce a CNC system with open source code. It allows obtaining a machine control system with minimal time and monetary loss. Open architecture allows future modifications and upgrades to meet the needs of users and accepts machine programs from a wide variety of software packages. However this leads to a few drawbacks that need to be addressed. Firstly, the capabilities of open source systems (GRBL, Smoothieware), are most often limited to milling, laser processing and three-dimensional printing [5], [6]. And it leaves the same problem of obtaining the CNC software for other types of equipment. Apart from that algorithms used in most open source systems result in low machining accuracy and surface quality and need be improved. In the present paper a way to overcome the listed disadvantages while using open source CNC system is suggested i.e. to both achieve the solution that is universal for every type of machining and increases the processing efficiency.

The paper proposes the use of a modular approach in the CNC software development, when all the main functions of the CNC system are designed as separate program modules interacting via a unified program interface (Application Programming Interface, API). There are several developments in this area [7]–[9]. The distinctive feature of this particular approach lies in a high level of granularity, i.e. division of a CNC kernel into modules, including the trajectory planning stage and embedding it into existing CNC systems with open source code as a basis. Thus, the following advantages can be achieved:

- Ensuring the operation of various types of modular equipment on demand by integrating the CNC system from the required modules.
- Possibility of continuous improvement and modification of the system by replacing modules that affect processing efficiency.
- Minimization of development cycle.

The paper aims to obtain the part of a numeric control kernel (NCK) responsible for the trajectory planning, based on a modular approach. It is intended for application on universal modular equipment. The paper also considers the possibility of using an open CNC system as a basis for the modular kernel. The task at this stage of development is to obtain a motion planner for milling and laser processing in such a way as to ensure the possibility of importing the developed modules into the existing open source CNC system.

The paper is organized as follows. The first Section is dedicated to analysis of modern trends in CNC systems and universal equipment development. In Section II the main aspects of the proposed modular approach are disclosed and its advantages are listed and explained. In Section III the obtained trajectory planning library and its structure is described. In Section IV the possibility to import additional and replace existing modules into open CNC systems to ensure the effective operation of different types of processing is considered. Section V shows the universal modular equipment in development and simulation results of the obtained trajectory planner. Finally in Section VI further clarifications to the work of the developed motion planner are given, as well as directions for the ongoing development of algorithms.

II. Related Work

An active development of the methodology for creating universal equipment is currently taking place. The aim of most researches is to combine the capabilities of additive and subtractive machining, as well as other types of technological equipment.

Among the existing developments of universal equipment there can be mentioned a combination of Rapid Prototyping (RP) equipment (three-dimensional printer) and a milling machine [10]–[12]. Apart from that, there are works that aim at combining laser and milling processing in one machine tool [13]. For example, in [14] a scheme for combining a CNC system to produce hybrid equipment for Fused Deposition Modeling (FDM) printing and three-axis milling was proposed. However, since, in this case, neither hardware nor software was obtained using the modular approach, its application in other types of processing is significantly limited.

On the contrary, the capabilities of the modular equipment considered in the paper make it possible to create not only subtractive and additive machine tools, but also robots, sorting and marking machines, and other technological units. Obviously, due to the fact that the machine organs are reinstallable and are not fixed rigidly, the processing accuracy is lower than when using specialized equipment. However, since a prototype is usually being developed to show the general performance of a product, the capabilities of modular machines are sufficient enough for this purpose.

The requirements for the CNC system that can be used in modular equipment are directly related to the main areas of development in this field and include minimizing the development cycle by ensuring a cross-platform approach, using an open architecture and the possibility of code reuse [7], [15].

Grigoriev and Martinov [7], proposed an approach for scaling channels control during data transfer, which allows reduction of interpolation and cycle time of a programmable logic controller (PLC), aimed at multi-axis processing. It leads to the acceleration of data processing in a CNC system. However, this approach does not support scalability in terms of using the resulting CNC system for other types of machining other than multi-axis milling.

The closest to the proposed solution is a cross-platform CNC kernel obtained by Grigoriev and Martinov [16], which can adapt to multi-axis machining. Also in [17], a model of the control system of an assembly robotic system is proposed with the ability to customize the CNC functions for the required physical configuration. In this case, the core of the control system represents a single module, but the composition of the core itself is constructed as a black box, and modification of the trajectory planning and interpolation methods is not considered.

A. Methodology

An analysis of existing methods for the development of control systems and the possibility of their application in modular equipment was carried out.

The solution proposed in this paper includes the possibility to integrate a CNC kernel from separate modules-blocks with unified input data. When solving this problem, it is necessary to determine the required level of system granularity [18]. Determination of the optimal level of detailization affects the entire system architecture and should be defined at the design stage [19], [20]. At its minimum level, the system consists of a single unit, this approach does not imply modularity. At the maximum level of granularity, each small component of the system is handled individually, resulting in an extremely fine-grained system and non-integrated design [20]. In this work, at the highest level of detail, the program code is presented as a single motion planning module, and at the lowest level modules responsible for geometry analysis, speed control and interpolation can be distinguished.

The proposed modular solution will allow not only the possibility of fast configuration of a CNC system for the required equipment, but wide space for continuous improvement of processing efficiency by importing and modifying the NCK modules responsible for processing accuracy.

The method is based on the synthesis of the developed motion planning modules and the existing CNC system. Considering the architecture and the possibility of expanding the source code, the Smoothieware system was chosen for this study [5].

A motion planner was developed for its use in laser processing. The simulation of its performance was carried out using the Python programming language version 3.6.5, charts are made with the Matplotlib plotting library version 2.2.2 and calculations are made using Numpy library version 1.14.2. CPU's clock speed is 2.20 GHz, Random Access Memory volume is 4 Gb, operation system is 64-bit Windows 10.

III. Modular approach in CNC development

The possibilities of modular equipment are wide and allow obtaining different installations and machines by replacing physical modules. The potential is not limited to milling, turning, drilling and laser processing: it is possible to obtain a 3D printer, marker, sorter, industrial robot, etc. The operation of all types of machines is controlled by a CNC system.

From a functional perspective, a CNC consists of a Human-Machine Interface (HMI), a Numerical Control Kernel (NCK), and a Programmable Logic Control (PLC) [21]. The HMI is an interface between the CNC and the user that executes machine control commands, displays its status and offers functions for editing part programs for processing. The PLC block sequentially controls the spindle speed of the machine, change of workpiece, tool and processing of I/O signals. It controls the machine behavior, with the exception of servo control.

Finally, the NCK block interprets part programs and performs interpolation, position control, and error compensation. This unit drives and controls the machine servo drives. The paper's main focus is on the development of NCK.

Evidently, each type of equipment requires its own specific functions to be performed by the control system. Fig. 1 shows an example of needed trajectory planning modules for laser, milling and 3D printing. For each type of processing, certain sets of modules are preferred. Since the use of complex paths is more typical for laser processing and three-dimensional printing, in this case it is preferable to work with curves directly, without preliminary segmentation. Usually Non-Uniform Rational B-Splines (NURBS) are used. On the other hand, to reduce the computational complexity in milling, the approximation of curved paths by linear segments is often used. The use of segmentation or NURBS planning modules depends on specific requirements.

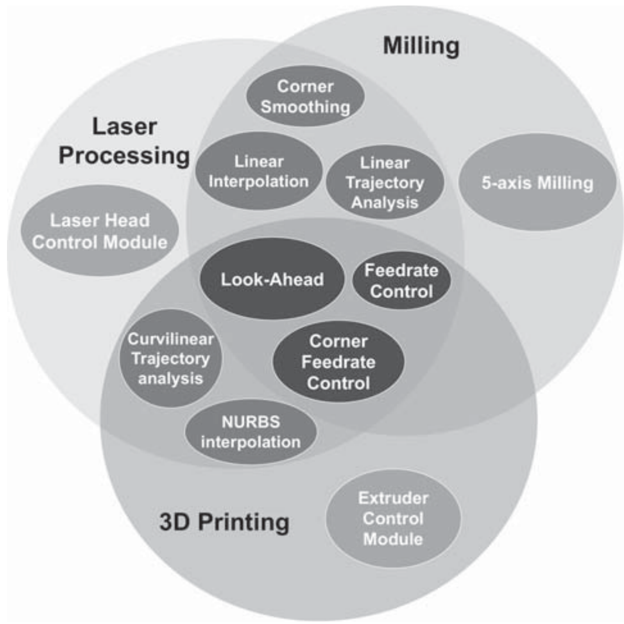

Fig. 1. Sets of modules for milling, laser processing and 3D printing

Apart from that, there are modules that are necessary to ensure equipment efficient operation. For example, the extruder control module allows providing the required material supply for 3D printing using FDM technology.

An approach to the development of CNC with a high level of granularity is proposed in this paper, when not only the main blocks of the system (Fig. 2 right), but also the NCK itself (Fig. 2 left) consist of separate modules-blocks, and the interaction between them is carried out through a unified Application Programming Interface (API).

Technological modules are optional and are used for certain types of processing or operations. For example, if a technology requires additional movement during the molding process (extruder control) or if the movement control is synchronized with devices such as laser head or electron beam gun.

The kinematic transformation module converts the coordinates according to the kinematic model of a machine. The use of the specific kinematic transformation is determined based on the kinematics of the machine.

Commands for controlling outputs and the status of inputs are integrated in the cyclic drive control data and are transmitted via the same interface. The trajectory planning phase is also divided into the following modules:

- Preliminary analysis of geometry.
- Acceleration/Deceleration control, during which the tool speed values are calculated for each interpolation period.
- Interpolation, where the control signals for drives that set the actuator in motion are generated.

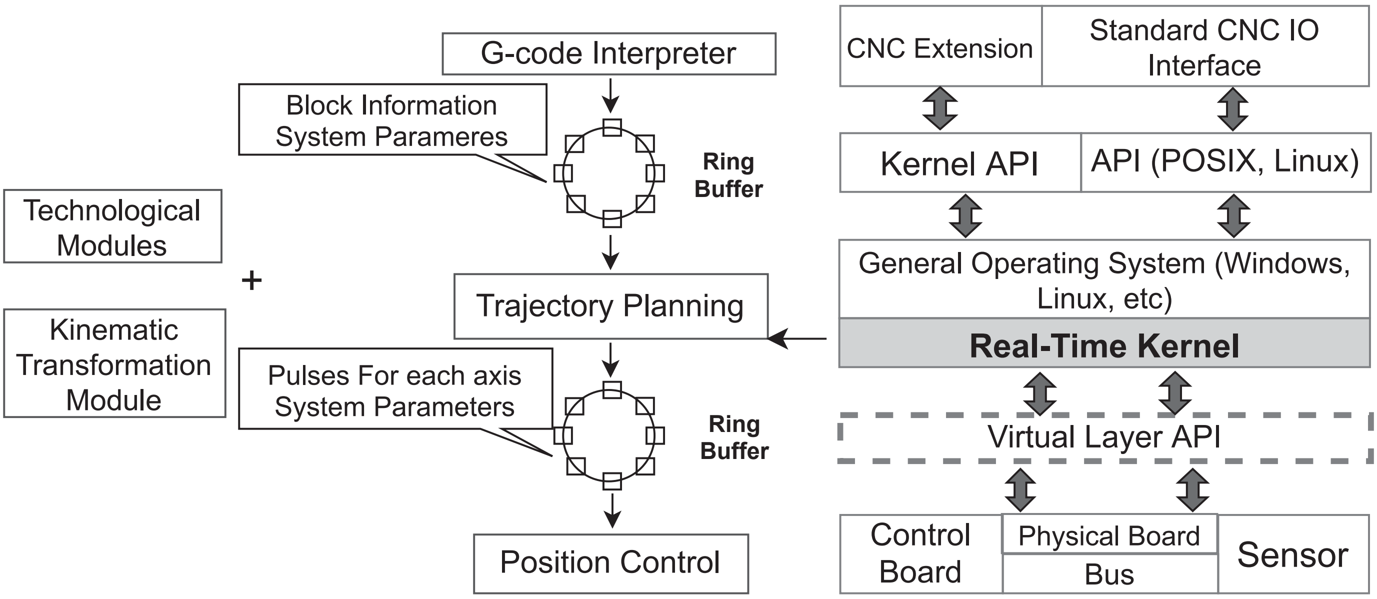

Fig. 2. The structure of CNC system (right) and NCK (left)

It is suggested to reduce the level of granularity and design each of the above stages of trajectory planning as a separate independent module. The main advantage of this modular approach is the ability to easily modify the existing algorithms by replacing modules that have the greatest impact on processing accuracy. Since the precision and speed of processing depends not only on the hardware of a machine, but also on the software component, the constant improvement of NCK algorithms will increase the equipment efficiency and the quality of the obtained part surface.

IV. Modular structure of NCK

As a result of practical aspect of the research, a motion planner software library for laser processing has been obtained, including modules for geometry analysis, speed control and interpolation. The structure of the library is shown in Fig. 3.

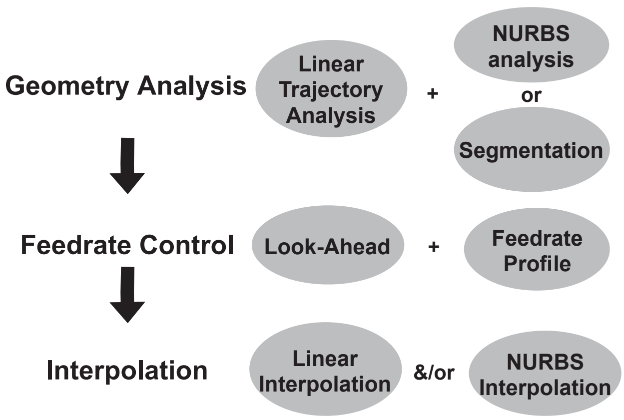

Fig. 3. The structure of developed trajectory planner

The modules can process both curvilinear trajectories and linear ones. The motion planner is designed in such a way that by adding appropriate modules (for example, NURBS interpolation), work with curves will be provided, which is necessary, for example, in 3D printers or in laser processing, where complex paths are often used. On the other hand, if it is replaced with a segmentation module, then all trajectories will be converted to linear segments, even if the original data in the control program is presented as curves, which decreases the time cycle and allows fast real-time processing.

The generation of a tool path begins after receiving data from the Interpreter module, where instructions of a part program are decoded and translated into the parameters of the tool trajectory.

Since the obtained data must be further analyzed before proceeding to interpolation, a set of modules for geometry preprocessing was developed. It includes the calculation of length of trajectory segments, corners smoothing, NURBS curves analysis or its segmentation with linear segments.

It should be noted that the trajectory contains tangential discontinuities at the corners between the linear segments. The module implements rounding with Bezier curves with six control points or exact traversal of the corner with a complete stop of the tool, depending on requirements. The allowable speed on the rounding is also calculated, taking into account the geometry of a parametric curve (curvature extremum) and allowable speed and acceleration. The detailed rationale for the choice of algorithms and methods for corner smoothing is given in one of the previous papers [22].

Also, when analyzing curvilinear trajectories at this stage, the trajectory can be divided into linear segments, if the segmentation module is selected, or the curvature of a NURBS curve can be analyzed to select areas where restrictions on the tool speed should be imposed so as not to exceed the allowable acceleration.

After geometry preanalysis, the speed or acceleration/deceleration control is executed, which consists in calculating the velocity values for each interpolation period T. To ensure accurate movement of the actuator during high-speed machining, the equipment must operate at speeds up to 600 mm/s with acceleration up to 2g. Acceleration/deceleration control consists of two main modules/stages: a speed profile generation of the current segment and Look Ahead algorithm.

First, the Look-Ahead module is executed, which calculates the start and end velocities for the current segment by analyzing the parameters of the next N segments. The N value is defined in the system parameters.

Further, the module for speed profile calculates a gradual change in speed along a segment. Based on the set feedrate, starting and ending velocity, and the allowable acceleration and jerk, the speed values for acceleration, deceleration and constant speed stages are calculated for each interpolation period T.

Finally, the interpolation is executed, which acts as a generator of the axial movement of the actuator based on data obtained during previous planning stages. Linear segments are processed according to the linear Reference Word interpolation algorithm. Curved segments and arcs, if not segmented at the stage of geometry analysis, are processed according to the second-order Taylor's expansion of the curve parameter with respect to the arc-length. Detailed rationale and description of interpolation algorithms used are presented in one of the previous papers [23].

The software is assembled from blocks that interact through a unified API. The use of a cross-platform kernel ensures the software independence from a specific platform and provides ample opportunities for CNC system configuration.

V. Possibilities for open CNC systems modification

One of the advantages of modular CNC development is the ability to integrate the developed modules into existing open source systems. The study considers the possibility to use the Smoothieware CNC system, developed for the 32-bit SmoothieBoard by a team of volunteers [5]. Its main benefit is the ability to extend the existing source code.

The structure of Smoothiewave NCK, input and output at each stage of trajectory planning are shown in Fig. 4. Since the interchangeability of modules in this system is carried out through a unified API, additional modules can be imported or replaced to improve processing efficiency. Fig. 4 also shows possibilities for replacement of existing and import of additional modules of path planning to ensure increased accuracy and processing speed.

This approach is beneficial for the following reasons:

- It reduces the time for software development, since the basis of the CNC system already exists.
- It helps to adjust the system to the required hardware, i.e., when replacing physical blocks in universal modular equipment, by adding necessary programming modules.

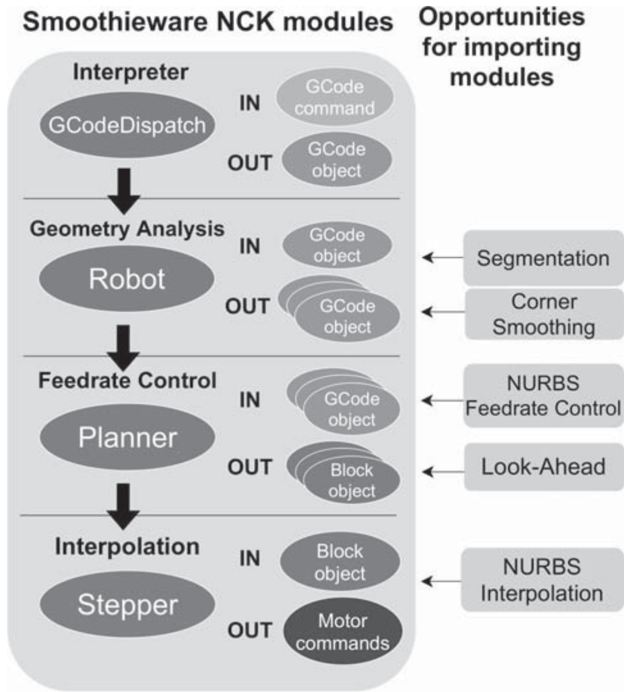

Fig. 4. Possibilities for Smoothieware CNC system modification

- It gives the opportunity to import modified algorithms of part program analysis and trajectory generation to improve the accuracy and speed of machining.

The paper suggests embedding previously developed modules that have the greatest impact on processing accuracy into the existing CNC. Among these modules the tool trajectory generation, feedrate control and interpolation can be mentioned. The interchangeability of modules is carried out through a unified API, which allows fast redesign of a system depending on the hardware requirements. This approach will significantly simplify and improve processing efficiency when using modular equipment.

Since most open systems offer the possibility of upgrading and extending the source code, a similar approach can be applied to systems other than Smoothieware. However, the architecture of this system turned out to be the most suitable for applying the proposed approach.

VI. Simulation results

The suggested approach and modules, described in Section III are used for designing a control system for a prototype of the modular technological equipment platform, which is shown in Fig. 5. At this stage of development, it is possible to implement laser and measuring equipment, three-dimensional printing using FDM technology, as well as milling and drilling processing of aluminum alloys [24]. The modular platform consists of a two-axis table with the possibility of setting an additional third axes. Work space size is 500×500 mm, a servo-step drive is used. The tool moves by means of a ball screw and cylindrical guides with linear rolling bearings.

One ball screw is installed on the X axis, two on the Y axis, synchronized by a belt drive.

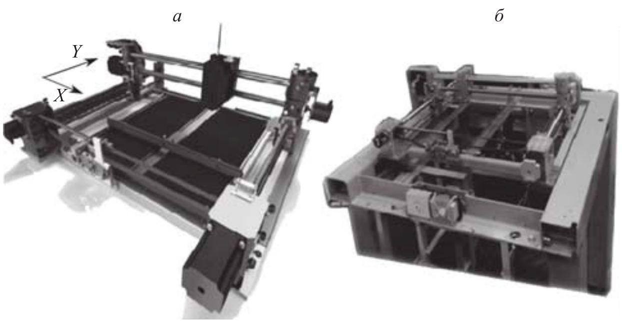

Fig. 5. Platform in Solidworks (a) and assembled (b) [24]

A Smoothieboard circuit board with a Smoothieware control system is used for controlling the platform operation. The modules responsible for the trajectory generation in the system have been replaced with the described above in Section III.

Simulations of the obtained software library were carried out. The following sample tool path has been used as an input: curvilinear trajectory with unit weights and a nodal vector K = [0, 0, 0, 0, 0.25, 0.5, 0.75, 1, 1, 1, 1] (Fig. 6, a). Required feed was set as F = 50 mm/s, maximum acceleration – A_{max} = 2,000 mm/s^2, maximum jerk – J_{max} = 20,000 mm/s^3.

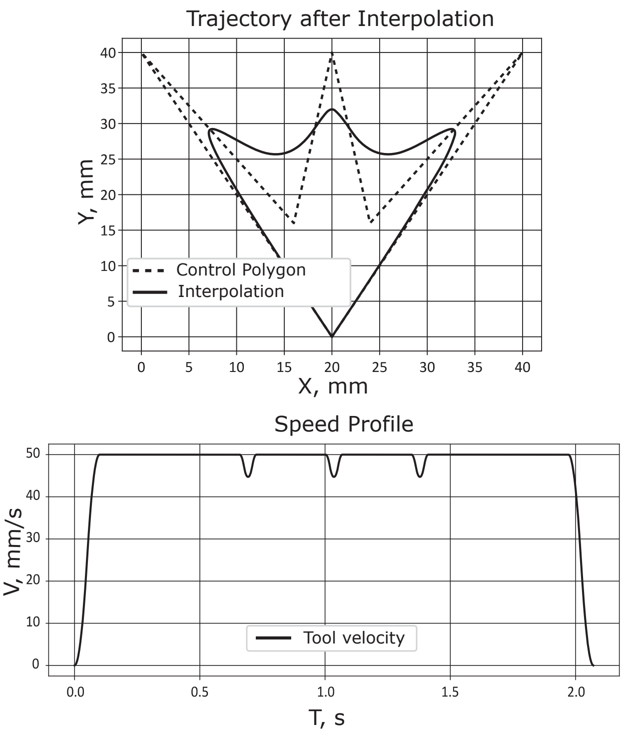

Fig. 6. Simulation example

The curve is interpolated directly, without preliminary approximation. The resulting velocity profile, where V is tool speed, mm/s; T - time, s, is shown in Fig. 5, b. The resulting linear processing error is within 17 μm, and the contour error does not exceed 7 μm, which is significantly less than the error that occurs when planning a similar trajectory in the Smoothieware system, where, among other things, preliminary segmentation of the original curve is required.

The resulting modules can receive data from the Smoothieware G-code interpreter as input. The generated output represents a class instance that contains the speeds and displacements required to generate control signals for drives. In this form, they can be used by the corresponding modules of Smoothieware system to control the tool movement.

VII. Discussion

The proposed approach can significantly increase the competitiveness of small organizations. It should be addressed that, in contrast to the proposed solution, it is possible to develop a universal CNC system that is not based on a modular approach, which will already contain all the required functions for any type of processing. In this case, there is no need to import additional modules. However, without modular approach, the possibility of modifying the algorithms is significantly complicated. And the large number of modules in such system can create difficulties in management and interaction.

The developed planner described in Section III successfully generates trajectories consisting of linear segments, circular arcs and curvilinear NURBS paths. Due to the versatility of the trajectory representation, this module can be applied both for segmented trajectories, and for part programs with direct curves representation.

All received deviations between desired and resultant trajectories are of small order and are comparable with the results of other developments and the performance characteristics of commercial machine tools of the middle price category. A smooth velocity profile with jerk considered, as well as parametric interpolation of curvilinear trajectories with division into equal segments, made it possible to minimize tool speed inconsistencies and vibrations.

Despite the fact that the developed software library was focused on laser processing, it is also possible to use it for milling, for this it is necessary to change some system parameters, such as permissible acceleration and jerk: for milling, their value must be reduced by an order of magnitude.

Finally, to further expand the capabilities of a modular installation, it is necessary to develop modules for other types of processing, including, for example, technological and kinematic transformation modules. It is required to form a list of required modules for the successful operation of each type of modular equipment.

As for practical application, it is assumed that employees of a small design organization could acquire the required modules for a modular platform of technological equipment and the Smoothieware system with a built-in motion planner developed within the framework of this work. In the future, it would be possible to develop other modules and improve the existing ones on the basis of the proposed approach to ensure the operation of various types of equipment and to improve the quality and accuracy of processing. Interchangeability and a high level of granularity, together with documentation, makes it easier to work with the code in the case of possible development team changes.

Plans for further research include the development of other modules to expand the modular equipment capabilities. Among them is an algorithm for generating drive pulses for motors, as well as an interpreter of G-codes and a feedback system (position control) to improve the existing open source software and possibly use the modules independently, and not as part of the existing CNC system. Also plans for further work include the development of an error compensation system for curved paths to improve processing accuracy.

Further areas of development may also include the modification of a CNC system to a Cyber-Physical Machine Tool (CPMT), which was proposed in [25] to enable continuous monitoring and control of the machining process. It is especially important in the case of modular equipment since the physical modules are not rigidly fixed ant there is higher possibility of change of their relative position during processing, which requires additional monitoring.

VIII. Conclusion

The paper proposes an approach to the development of an NCK of a CNC system, which allows integrating the required software from programming blocks for the use on modular equipment. The possibility of using existing open source CNC system Smoothieware as a basis was also considered and the modules required for each type of machining can be imported there. In this case, there is no need to develop a system from scratch, and it also becomes possible to modify existing algorithms that affect the processing accuracy to improve the efficiency of the processing.

A motion planner, including modules for geometry analysis, acceleration/deceleration control and interpolation, was obtained. The simulations show low contour and linear error while maintaining high processing speed. The resulting modules can be imported into the CNC system Smoothieware to improve the efficiency of existing algorithms, e.g. allow direct processing of complex curvilinear trajectories without negative consequences of segmentation. Also, the application field of the algorithm is not limited to laser processing, but can also be used for milling.

It is proposed to use the obtained planner for modular equipment, when the required installation is formed from separate physical blocks. In this case, it is possible to ensure the operation of the CNC system, depending on the hardware requirements. All the listed advantages of the development distinguish it favorably among the available open source projects.

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