Design and Development of High-Precision Hybrid Controller for Ultra-Precision Non-Conventional Single-Point Diamond Turning Processes

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ABSTRACT:
Ultra-High precision Single-Point Diamond Turning (SPDT) is a widely used machining technology for generation components with optical grade surfaces. SPDT has been widely used in different industry sectors including aerospace, biomedical, military, defense, electronics, and entertainment. By using SPDT, manufacturing of optical surfaces with roughness down to one nanometer, even less than one nanometer, is possible. Recently, the application of non-conventional SPDT techniques during SPDT for improving the outcome of the process has been emerging. Non-conventional machining techniques have been developed and used during SPDT for assisting the process from different capacities. It has been revealed that by using a sole or a combination of non-conventional techniques during SPDT, superior results in terms of optical surface roughness and surface profile accuracy could be obtained. However, non-conventional SPDT technologies are novel solutions and more research need to be undertaken in terms of optimizing these processes and improving their performance. In this study, a novel high-precision hybrid controller is designed and developed for using in non-conventional SPDT processes. The proposed hybrid controlled has the capability of automatically and precisely control different non-conventional machining techniques during the diamond turning process. This controller could be used in a hybrid SPDT platform for controlling implemented machining techniques and synchronizing them. In addition, this hybrid controller could connect to on-machine metrology devices for in-process data acquisition, analyzing process parameters, and determining machining conditions. Thus, in-process tuning of the working parameters is possible. Results of simulations and experimental study have shown the functionality of the developed controller with sufficient precision to be used in such ultra-precision non-conventional SPDT processes.

KEYWORDS: Ultra-Precision Machining, Hybrid Machining, Non-Conventional Machining, Single-Point Diamond Turning, Control System, Hybrid Controller.

1. INTRODUCTION

Ultra-high precision machining methods are widely used in advanced manufacturing of critical components. Single-Point Diamond Turning (SPDT) is one of the most accurate machining techniques for cutting surfaces with accuracy down to one nanometer, even less than one nanometer [1-3]. This ultra-precision machining technique has been extensively used in different fields of industry including biomedical products, body implants, optical products, defense, military, aerospace, electronics, and entertainment [4-7]. Fig. 1 illustrates a standard SPDT platform. Different advanced mechanisms and high-precision systems are used in development of SPDT machine platforms.

The application of using high-precision control units for controlling the performance of the machining processes in an important term in advanced manufacturing. A large number of research and experimental studies have been performed for developing high-precision controllers to be used on SPDT platforms, for controlling the machining process and setting machining parameters while enabling various machining conditions [8-11].

In standard purely mechanical SPDT process different factors may influence the diamond turning process and limit the optical surface generation. Recently, non-conventional machining techniques have been specifically designed and developed to be used during SPDT for impacting the workpiece and/or machine-tool [12-16]. In non-conventional assisted SPDT techniques, a control unit is implemented within the system, for controlling the performance of the system and setting working parameters of the system. These systems should be able to automatically control the machining process. In case a closed loop control system is implemented, the control system would have the capability of tuning the machining parameters for setting optimized machining conditions during the turning process [17-22].

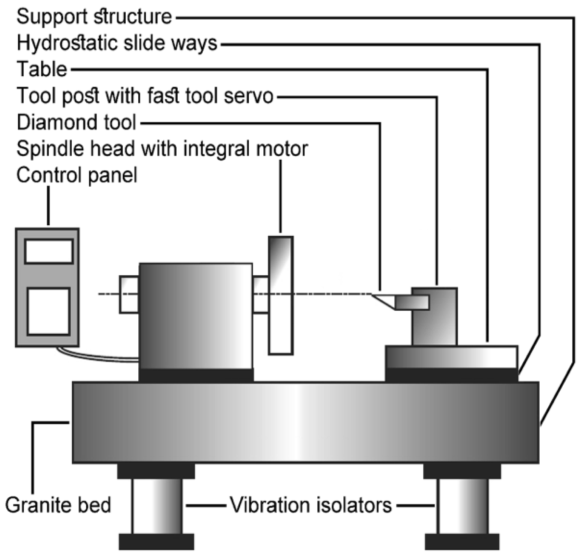

Fig. 1. A typical single-point diamond turning machine components [1].

Recently, the application of using combined techniques by integrating non-conventional machining methods have been emerging. In a hybrid SPDT platform, more than one machining technique are assisting the cutting mechanisms. These techniques work simultaneously and impact the diamond turning process from different aspects. Therefore, for enabling a fully automatic procedure while automatically setting and optimizing machining parameters, a hybrid control unit is required.

In addition, during non-conventional SPDT processed, in-process metrology systems for measuring and diagnosing errors, as well as monitoring the machining conditions could be implemented. The hybrid control unit is required to have the capability of communication with on-machine metrology systems for acquiring the captured data, analyzing them, and accordingly, tuning the performance of the working systems [23]. Measuring different machining parameters would provide a better perspective of the behavior of SPDT and the effect of influencing factors on optical surface generation. In addition, metrology systems can enable testing machining conditions and their influence on surface generation using new aspects of SPDT technology [19], [24-29].

In this study, a Multi-Axis Automatic Hybrid Controller (MAAHC) is designed and developed to be used in non-conventional SPDT processes. The proposed MAAHC has the capability of controlling non-conventional machining techniques and on-machine metrology devices. By using the MAAHC in a hybrid SPDT platform, controlling the performance of the implemented non-conventional machining techniques, setting machining parameters, and tuning the machining factors during the turning process is possible. In addition, the controller has the capability of connecting to the on-machine metrology systems for acquiring the measured data, analyzing the data, and optimizing machining conditions via tuning the under-control systems. In following sections, the design and working principles of the developed MAAHC have been introduced. Subsequently, the results of experimental studies performed have been illustrated and the results obtained have been discussed. At the end, the main findings of this research have been drawn and guidelines for future works have been suggested.

2. DESIGN AND DEVELOPMENT OF HIGH-PRECISION HYBRID CONTROLLER

The main application of using a hybrid controller on a non-conventional SPDT platform is to control the performance of the implemented non-conventional and hybrid machining techniques. The non-conventional technologies that have been used in non-conventional assisted SPDT processes are listed as follow:

1) Active vibration systems could assist the SPDT process by applying mechanical vibrations and enabling intermitted cutting of the workpiece surface. Slow-tool-servo, fast-tool-servo, and ultrasonic vibration systems have been widely used during SPDT. Applying a vibration solution during the turning process could decrease the diamond tool wear and improve optical surface generation mechanisms [30-33]. In these systems, by controlling the frequency of trigger signals, the frequency of mechanical vibration could be precisely controlled.
2) Hot machining systems including laser beam systems and furnace chambers could assist the SPDT process physically. By using a hot machining technique, the workpiece surface temperature could be increased to a specific level before or during the diamond turning process. Using a hot machining solution during SPDT would result in decreasing cutting forces and tool wear while improving the optical surface roughness of the cut materials. In addition, by using a hot machining technique, the brittleness of the material could be improved [34-36]. By using high-power AC and DC switching and control signals, the performance of hot machining systems could be precisely controlled.
3) Nitrogen cold plasma jet, as well as gas shielding techniques could assist the SPDT process by providing a gas shielding during the diamond

turning process. These techniques could reduce the chemical affinity of the free carbons of the workpiece surface and diamond tool. Thus, tool wear of the diamond tool, optical surface roughness, and surface profile accuracy could be improved [37, 38]. By using high-power AC and DC switching and control signals, the performance of gas shielding systems could be precisely controlled.

4) Applying an external magnetic field around the cutting zone during SPDT could influence the process physics and provide more stable turning conditions. Applying magnetic field around the workpiece and machine-tool could also improve thermal conductivity of the paramagnetic materials and positively influence machining factors including cutting temperature and material swelling [39-41]. In this context, by using high-precision linear movement systems, the position of implemented magnets in both sides of the machine's spindle could be adjusted for centering the magnetic field or its intensity.

Therefore, the hybrid controller needs to have the capability of connecting to the implemented non-conventional machining systems and controlling their performance. Fig. 2 illustrates the working principles of the MAAHC.

The MAAHC consists of different units which work independently and simultaneously, for enabling the control and synchronization of different machining processes. In this controller, three microcontroller boards are implemented while performing different tasks independently in a synchronized manner.

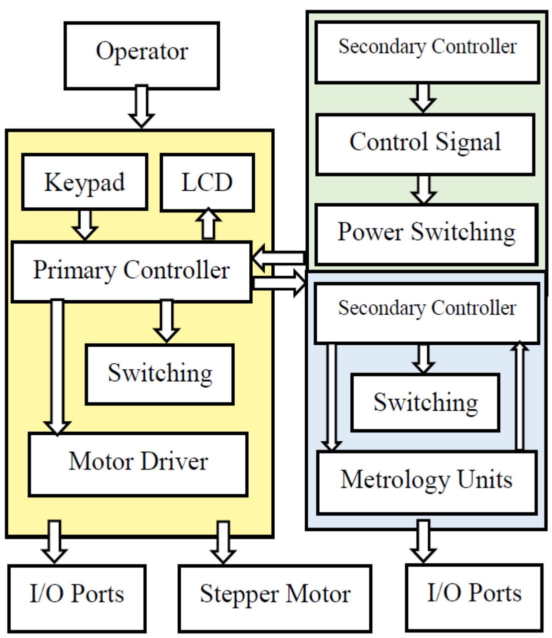

Fig. 2. Schematic diagram of the developed MAAHC [42].

In this device, the main control units, called primary controller, is implemented for running the general tasks of the system while controlling and synchronizing the implemented secondary control units. A MEGA-2650 REV3 MCU development board with ATmega2560 RIS-based microcontroller is used as the primary control unit. This microcontroller board provides 54 digital I/O ports including 14 PWM outputs, 16 analogue inputs, with 4 universal asynchronous receiver-transmitter (UART) ports and16 MHz of clock speed.

The analog and digital I/O ports could enable the capability of communicating with the implemented non-conventional machining techniques while controlling their performance precisely by using different solutions. The main application of these Input / Output (I/O) ports is sending the control signals for running the implemented non-conventional machining techniques including gas shielding systems, hot machining systems, and active vibration systems, as well as executing control signals for driving motors in linear axes.

A liquid crystal display (LCD) is connected to the primary controller for monitoring the set machining parameters and machining conditions. In addition, a keypad is connected to the primary controller for enabling setting required machining factors before the machining process. The set factors could also be modified during the process by using these human-machine interfaces. In addition, the primary controller is connected to high-performance electronic switching ports for enabling real-time controlling the performance of implemented non-conventional machining systems.

Two L298 dual full-bridge motor driver boards are implemented while providing 8 control ports for executing high-power control signals for driving the various motors including stepper motors, DC motors, and servo motors. The primary controller is connected to motor drivers and transmits control signals with predetermined sequences for driving implemented motors. By using a precision linear control system, Multi-Axis Automatic Controller (MAAC) [43], driving and controlling two hybrid stepper motors in two independent linear axes with maximum accuracy of 7.6 nanometer per step is possible [43, 44]. Alternatively, controlling and driving four DC or servo motors also becomes possible.

Two secondary control units are implemented in the MAAHC, which are illustrated in green and blue background in Fig. 2. In these units, an UNO-A000073 REV3 MCU development board with ATmega328 RIS-based microcontroller is used. This microcontroller board provides 14 digital I/O ports including 6 PWM outputs, 6 analogue inputs, with a universal asynchronous receiver-transmitter (UART) and clock speed of 16 MHz. These microcontrollers are connected to the primary control unit for data transmission and synchronization. The application of these two units are drawn as follow:

1) The control unit which is illustrated in the green background in Fig. 2, is specifically designed for generating a wide range of precise control signals from 1 Hz to 60 KHz. This signal generator is implemented for generating control signals for driving the implemented active vibration machining technique during diamond turning. Slow and middle range frequencies, typically under 10 KHZ, could be used in generating the control signals for slow and fast tool servo systems. Ultrasonic vibration systems have a wide range of application in non-conventional SPDT platforms for generating high-frequency mechanical vibrations with frequencies above 15 KHz. The generated control signals are then transferred to the high-power switching unit of the active vibration system. Thus, the system is capable of generating high-voltage signals with the frequency of input control signal. Therefore, controlling the performance and the frequency of generated mechanical vibrations by using MAAHC is possible.
2) The control unit which is illustrated in the blue background in Fig. 2, is specifically designed for connecting to on-machine metrology systems for controlling them and acquiring data with contains measured machining factors during machining process. In this unit, by using standard communication protocols, including serial data transmission and wireless data transmission solutions including WIFI and Bluetooth, communicating and data acquisition during machining process is possible. By using digital I/O and high-performance switching, controlling the performance of implemented on-machine metrology systems during hybrid SPDT processes is realised.

The specifications of the designed system including the schematics and electronic circuits design are previously published in a feasibility study on this hybrid controller [42]. The specifications and features of MAAHC are listed in Table 1.

The developed MAAHC has the functionality for enabling a precise control of the performance of non-conventional machining techniques, including slow- and fast-tool servo, ultrasonic vibration, laser beam, furnace, and gas shielding techniques, during different forms of non-conventional SPDT processes. Fig. 3 Illustrates the developed MAAHC controller. It could be seen that: (A) The active vibration systems could get connected to the control signal generator for generating a controlled high-power signal for driving the active vibration system. (B) The performance of the laser beam system could be controlled by MAAHC through I/O digital ports and switching gates. (C) The MAAHC has the capability of generating analog and digital signals; by using logic gates and switching ports, the performance of gas shielding techniques including nitrogen cold plasma jet could be precisely controlled. (D) By using the MAAC linear control system in design and development of MAAHC, stepper and DC motors could be derived and controlled precisely, with nanometric positioning accuracies. In addition, the MAAHC has the capability of communicating with on-machine metrology systems through standard data communication protocols for in-process measurement, analyzing, and tuning the working parameters of implemented machining techniques.

Table 1. Specifications of developed MAAHC.

Hybrid Controller	
Output power	2000 Watt
AC output voltage	220 AC
DC output voltage	0 – 24 V
DC output current	25 A
Signal generator output	5 VDC, 1 Hz - 60 KHz
I/O Ports	Analog / Digital Data
No. of Analog I/O	12 Ports
No. of Digital I/O	24 Ports
Standard communication protocols	Serial WIFI Bluetooth
Motor driver output	0-24 V
DC switching	2 Ports, < 800 KHZ
AC switching	2 Ports, < 800 KHZ

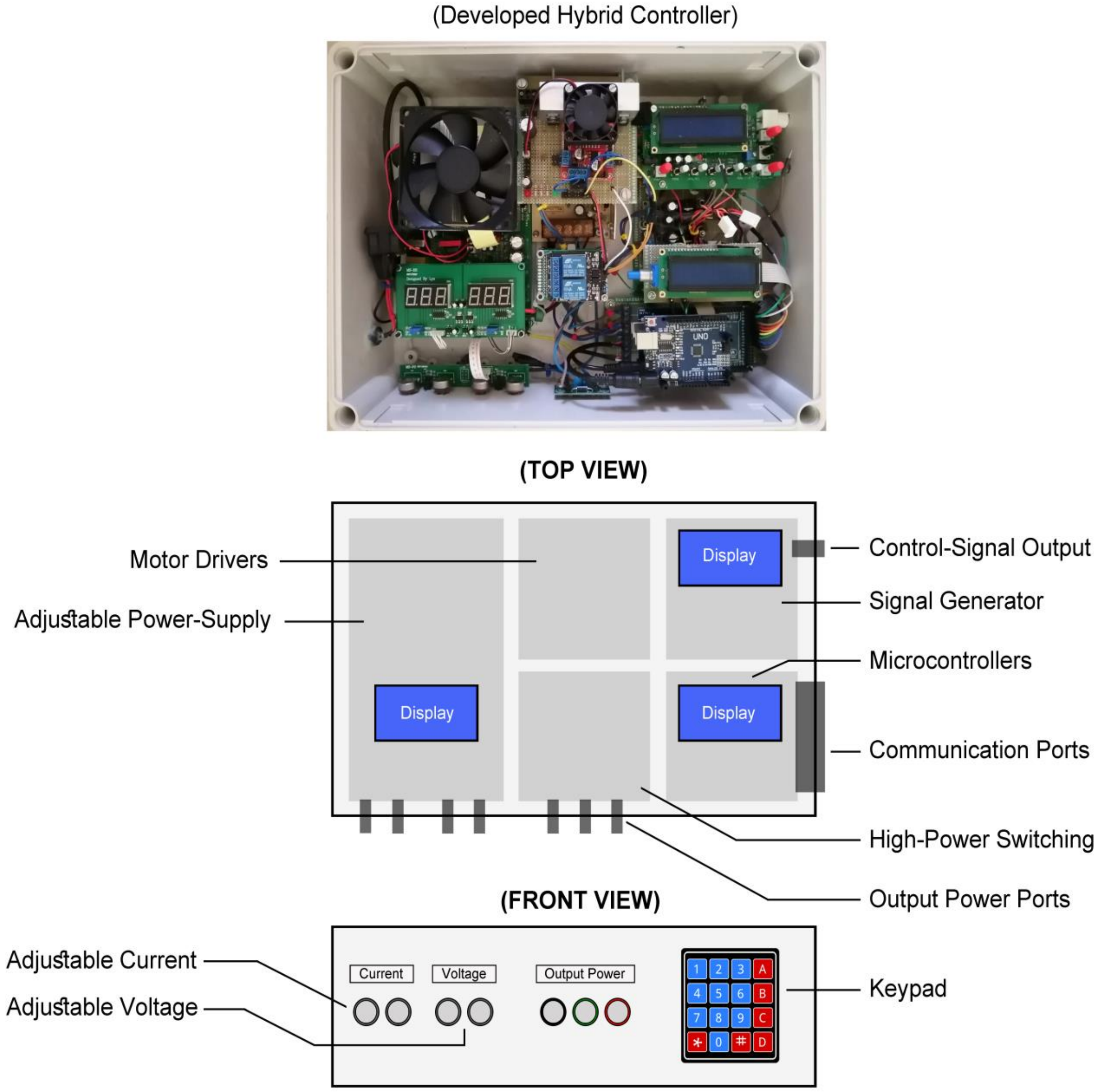

Fig. 3. The developed MAAHC and schematic views of the device.

3. RESULTS

The results of this study are divided into two main groups; the results of performed simulations, and the results of experiments using a bench test based on the MAAHC developed. The obtained results are presented in the following subsections.

3.1. Modeling and simulations

For evaluating the designed system, simulations have been performed using MATLAB/SIMULINK software. The detailed overall design of the developed MAAHC, as well as the generated output signals of the system been presented in a previously published work by authors [42]. Simulation results have shown that the designed MAAHC has the capability of controlling and driving precision hybrid stepper motors in two independent linear axes, with maximum movement accuracy in micro-stepping mode [42]. From the obtained simulation results it could be deduced that the designed control system has the necessary stability, repeatability, and functionality of the driving stepper motors with sufficient linear positioning precision. In addition, the performance of the digital I/O ports and the capability of the MAAHC in generating different frequencies of control signals have been proved to be precise enough [42]. Therefore, the application of developing such a MAAHC proved to be feasible.

3.2. Experimental results

The MAAHC has been connected to measurement systems and analog and digital inputs have been transmitted to the MAAHC to evaluate the performance of the device and to analyze acquired data. A two-channel 60 MHz RS Pro RSHS800 Series digital oscilloscopes was used in the experiment for acquiring the waveform of control signals generated, as well as high-power switching DC outputs. Screenshots of the oscilloscope's display have been captured during the experiment. In the MAAHC, two high-power digital switching port are implemented for switching high-power DC voltages with high frequency, between 80 KHz to 800 KHz, for controlling and driving the systems used in a hybrid SPDT solution. Fig. 4 illustrates the performance of the these switching ports. In this phase of experiment, output voltages, 5 VDC, square-waveforms, with frequency of 80, 100, 300, and 800 KHz have been generated.

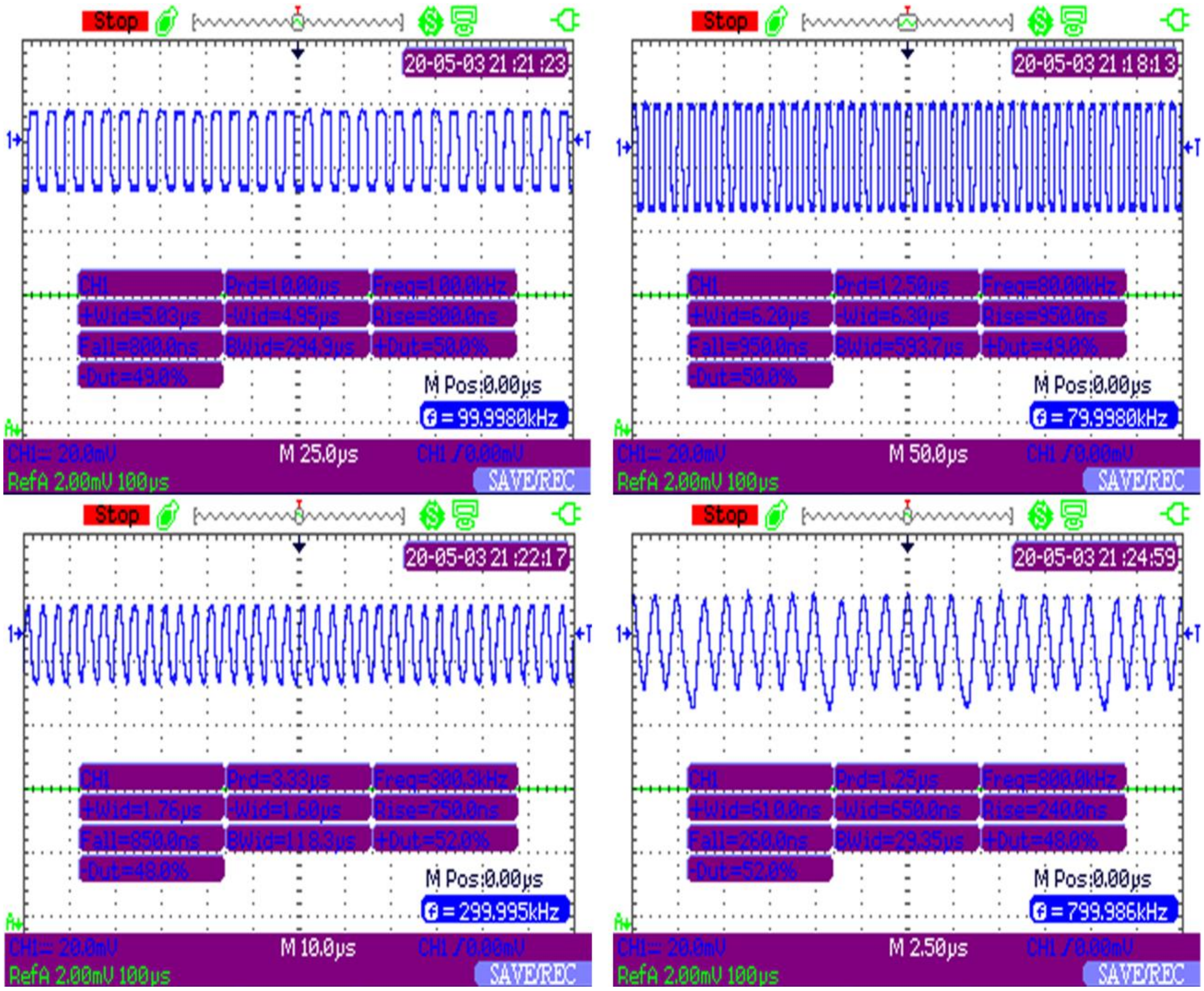

Fig. 4. The performance of switching ports.

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In the MAAHC, for controlling and driving active vibration systems, a precise signal generator is used for generating precise control signals, triggering the active vibration systems, and generating mechanical vibrations with specific parameters. This unit is capable of generating controllable signals in a wide range of frequencies from 1 Hz to 60 KHz. With regard to the range of vibration frequency in active vibration systems, between 1KHz to 35 KHz, in this phase of experiment, control signals with frequency of 1 KHz, 5 KHZ, 10 KHZ, 20 KHz, 25 KHz, and 40 KHz have been generated. After the working parameters are set in the MAAHC, the system is run for generating the control signals with the predetermined frequencies. Fig. 5 illustrates the output signals generated by MAAHC and captured by the oscilloscope. It can be seen that this unit could successfully generate precise control signals in a wide range of frequency from 1KHz to 40 KHZ.

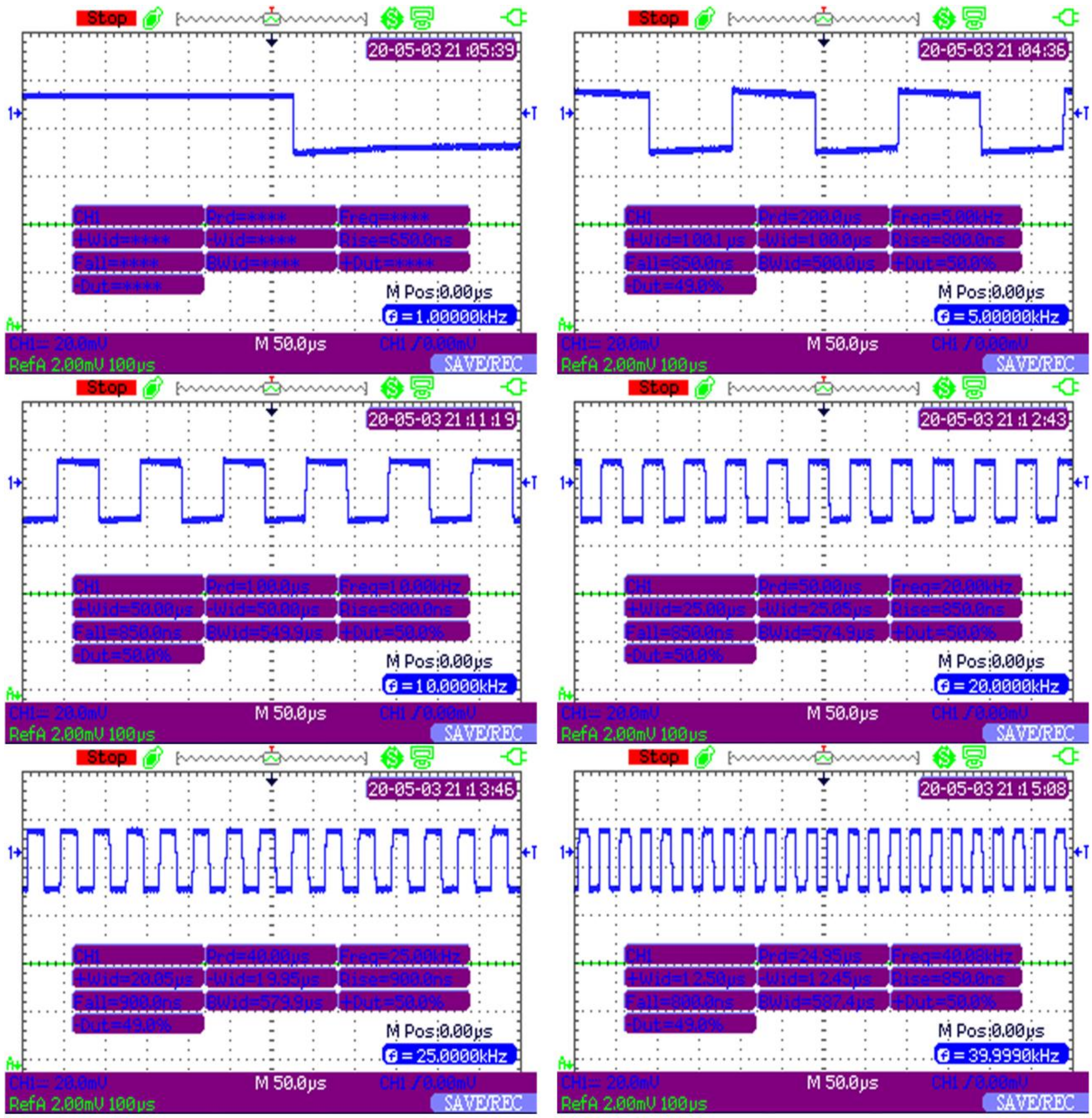

Fig. 5. The generated control signals for driving the active vibration systems: 1 KHz, 5 KHz, 10 KHz, 20 KHz, (D) 25 KHz, and 40 KHz.

In addition, the MAAHC has the capability of in-process measuring of analog signals including cutting force. The MAAHC has been connected to a high-precision force sensor, with the precision of 0.1 N, for measuring applied forces via generated analog signals. An unstable force has been applied to the schematic tool tip. The system showed the capability of measuring cutting forces with precision of 0.1 N. The captured data containing the measured machining factors has been analyzed and then shown by the MAAHC.

4. DISCUSSION

In non-conventional machining technologies, the application of an automatic controller for controlling the machining processes is unavoidable. In SPDT, hybrid machining methods by using non-conventional machining techniques, as well as on-machine metrology systems for in-process monitoring of machining conditions have been emerging. However, there are still limitations and complications in such machining methods. More research needs to be performed on the different aspects of hybrid techniques including process control methods. In a hybrid SPDT platform, a hybrid controller needs to be specifically designed and developed for enabling a fully automatic process while controlling the additionally implemented machining techniques and metrology systems.

The developed MAAHC has the capability of controlling stepper, servo, and DC motors. By using a linear control system, the MAAC, precise controlling of the movements in independent linear axes is possible. Simulation results have shown that generated voltage and current waveforms are precise with 90 degree displacement between two phases of the stepper motor [42]. The MAAHC has also the capability of driving DC motors and servo motors with using MAAC open-loop control system [43]. With regard to the obtained results from simulations it could be deduced that the MAAHC has sufficient stability, repeatability, precision, and functionality of driving mentioned motors with sufficient linear positioning precision.

The control signal generator unit of the device could generate precise control signals for controlling the vibration frequencies of implemented active vibration systems. Results of experimental studies have revealed that the designed system could successfully generate precise control signals with desired frequency in a wide range between 1 Hz to 60 KHz. It could be seen in Fig. 5 that the generated control signals with different frequencies are completely precise and aligned with the theory.

In addition, a variable power supply is implemented for providing AC and DC voltages. By using I/O digital ports, high-power switching, and variable power supply, different modes for controlling implemented systems is well covered. By using these features, a precise control on the implemented hot machining solutions and gas shielding techniques is possible. Results of experimental study, illustrated in Fig. 4, show the performance of switching ports in switching AC and DC voltages.

On-machine metrology systems could also get connected to the MAAHC via standard data transmission protocols including serial, WIFI, and Bluetooth protocols. The MAAHC also could get connected to analogue and digital sensors for acquiring data for distinguishing machining conditions. By using analog and digital I/O ports, acquiring the measured data from is possible.

Therefore, it could be deduced that the developed MAAHC has the required functionality with high-precision performance, which could enable using this controller in hybrid SPDT platforms.

5. CONCLUSIONS AND FUTURE WORK

Ultra-precision machining is the recent realm subsequent to conventional machining for advanced manufacturing of critical components for different industry sectors. Ultra-precision SPDT has been widely used for manufacturing of optical components with surface roughness down to one nanometer. Recently, the application of non-conventional machining techniques and surface metrology devices for using in combined SPDT platforms have been emerging.

In non-conventional assisted SPDT and hybrid SPDT processes, a precise controller is required for in-process controlling the performance of the operating systems, synchronizing their performance in controlled and predetermined sequences, and real-time tuning their machining factors. The application of non-conventional SPDT processes has been recently emerging. More research needs to be undertaken towards enabling an ultimate hybrid SPDT solution, where, all implemented techniques could positively impact the machining process in a fully automatic procedure in precise and predetermined sequences, in which the performance of each implemented system is precisely controlled.

In this study, a multi-axis automatic controller (MAAC) has been designed and developed to be used in non-conventional SPDT processes for controlling the performance of individual non-conventional machining techniques and communicating with on-machine metrology systems. The results of simulations and experimental studies show that the developed MAAHC has a good functionality to control different machining techniques while providing enough precision with regard to controlling their performance and setting machining parameters.

The developed MAAHC has the capability of controlling active vibration systems, and parameters of hot machining and gas shielding techniques. In future study, the MAAHC controller could be implemented in hybrid SPDT processes and get connected to implemented non-conventional machining techniques and metrology systems; for enabling fully automatic machining processes and setting the optimized parameters real-time during SPDT. Using such hybrid combinations will improve the machining behaviors of difficult-to-cut materials and the outcome of the various metal cutting processes.

In addition, with regard to the capability of MAAHC in wireless communication with other systems; in the future development on this hybrid controller, a software could be developed and installed on a computer or tablet, for controlling the performance of the MAAHC and performing real-time monitoring of the machining conditions while saving the measured data for further off-line research and analyses.

REFERENCES

[1] Hatefi, S. and K. Abou-El-Hossein, **"Review of Single-Point Diamond Turning Process in Terms of Ultra-Precision Optical Surface Roughness".** The International Journal of Advanced Manufacturing Technology, Vol. 106, No. 5, pp. 2167-2187, 2010.

[2] Abdulkadir, L.N., et al., **"Review of Molecular Dynamics/Experimental Study of Diamond-Silicon Behavior in Nanoscale Machining".** The International Journal of Advanced Manufacturing Technology, Vol. 98, No. 1-4, pp. 317-371, 2018.

[3] Mishra, V., et al., **"Ultra-precision Diamond Turning Process, in Micro and Nano Machining of Engineering Materials".** Springer. pp. 65-97, 2019.

[4] Ming, W., et al., **"A Comprehensive Review of Theory and Technology of Glass Molding Process".** The International Journal of Advanced Manufacturing Technology, pp. 1-36, 2020.

[5] **Zhang, S., et al., "A review of Fly Cutting Applied to Surface Generation in Ultra-Precision Machining".** International Journal of machine tools and manufacture, Vol. 103: p. 13-27, 2016.

[6] Zhang, S., et al., **"A Review of Surface Roughness Generation in Ultra-precision Machining".** International Journal of Machine Tools and Manufacture, Vol. 91, pp. 76-95, 2015.

[7] Sharma, V., M. Dogra, and N. Suri, **"Advances in the Turning Process for Productivity Improvement—a Review".** Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 222(11), pp. 1417-1442, 2008.

[8] Short, M. and K. Burn, **"A Generic Controller Architecture for Intelligent Robotic Systems".** Robotics and Computer-Integrated Manufacturing, Vol. 27, No. 2, p. 292-305, 2011.

[9] Chen, Y.-L., et al., **"Auto-tracking Single Point Diamond Cutting on Non-Planar Brittle Material Substrates by a High-Rigidity Force Controlled Fast tool servo".** Precision Engineering, Vol. 49**,** pp. 253-261, 2017.

[10] Ulmer Jr, B.C. and T.R. Kurfess, **"Integration of an Open Architecture Controller with a Diamond Turning Machine"**. Mechatronics, Vol. 9, No. 4, pp. 349-361, 1999.

[11] Zhu, W.-L., et al., **"Modeling and Analysis of Uncertainty in On-Machine Form Characterization of Diamond-Machined Optical Micro-Structured Surfaces".** Measurement Science and Technology, Vol. 27, No. 12, pp. 125017, 2016.

[12] Liu, X., et al., **"Analysis of Surface Texturing in Radial Ultrasonic Vibration-Assisted Turning".** Journal of Materials Processing Technology, Vol. 267**,** pp. 186-195, 2019.

[13] Langan, S.M., D. Ravindra, and A.B. Mann, **"Process Parameter Effects on Residual Stress and Phase Purity after Microlaser-Assisted Machining of Silicon".** Materials and Manufacturing Processes, Vol. 33, No. 14, pp. 1578-1586.

[14] Banik, S., et al., **"Recent Trends in Laser Assisted Machining of Ceramic Materials".** Materials Today: Proceedings, Vol. 5, No. 9, pp. 18459-18467, 2018.

[15] Li, Z., et al., **"Ultrasonically Assisted Single Point Diamond Turning of Optical Mold of Tungsten Carbide".** Micromachines, Vol. 9, No. 2, pp. 77, 2018.

[16] Fortunato, A., et al., **"A Laser Assisted Hybrid Process Chain for High Removal Rate Machining of Sintered Silicon Nitride".** CIRP Annals, Vol. 64, No. 1, pp. 189-192, 2015.

[17] Bhowmik, S. and D. Zindani, **"Combined Variant of Hybrid Micromachining Processes, in Hybrid Micro-Machining Processes".** Springer. pp. 61-70, 2019.

[18] Bhowmik, S. and D. Zindani, **"Overview of Hybrid Micro-manufacturing Processes, in Hybrid Micro-Machining Processes".** Springer. pp. 1-12, 2019.

[19] Luo, X. and Y. Qin, **"Hybrid machining : Theory, Methods, and Case Studies".,** London [etc.]: Academic Press, 2018.

[20] Chavoshi, S.Z. and X. Luo, **"Hybrid Micro-Machining Processes: A Review".** Precision Engineering, Vol. 41**,** pp. 1-23, 2015.

[21] Lauwers, B., et al., **"Hybrid Processes in Manufacturing".** CIRP Annals, Vol. 63, No. 2, pp. 561-583, 2014.

[22] Dandekar, C.R., Y.C. Shin, and J. Barnes, **"Machinability Improvement of Titanium Alloy (Ti–6Al–4V) via LAM and Hybrid Machining".** International Journal of Machine Tools and Manufacture, Vol. 50, No. 2, pp. 174-182, 2010.

[23] Li, D., et al., **"Kinematics Error Compensation for a Surface Measurement Probe on An Ultra-Precision Turning Machine".** Micromachines, Vol. 9, No. 7, pp. 334, 2018.

[24] Li, D., et al., **"Ultraprecision Machining of Microlens Arrays with Integrated on-machine Surface Metrology".** Optics express, Vol. 27, No. 1, pp. 212-224, 2019.

[25] Moretti, M., et al., **"Assessment of Surface Topography Modifications Through Feature-Based Registration of Areal Topography Data".** Surface Topography: Metrology and Properties, Vol. 7, No. 2, pp. 025003, 2019.

[26] Gao, W., et al., **"On-machine and in-Process Surface Metrology for Precision Manufacturing".** Ann. CIRP, Vol. 68**,** 2019.

[27] Troutman, J.R., et al., **"Machining and Metrology of a Chalcogenide Glass Freeform Lens Pair".** Procedia Manufacturing, Vol. 5**,** pp. 669-683, 2016.

[28] Bono, M.J. and R.L. Hibbard, **"Fabrication and Metrology of Micro-Scale Sinusoidal Surfaces in Polymer Workpiece Materials".,** Lawrence Livermore National Lab.(LLNL), Livermore, CA (United States), 2004.

[29] Balasubramaniam, R., R.V. Sarepaka, and S. Subbiah, **"Diamond Turn Machining: Theory and practice".,** CRC Press, 2017.

[30] Zhu, L., et al., **"Review on Fast Tool Servo Machining of Optical Freeform Surfaces"**. The International Journal of Advanced Manufacturing Technology, Vol. 95, No. 5-8, pp. 2071-2092, 2018.

[31] Kumar, J., **"Ultrasonic Machining—a Comprehensive Review".** Machining Science and Technology, Vol. 17, No. 3, pp. 325-379, 2013.

[32] Singh, R. and J. Khamba, **"Ultrasonic Machining of Titanium and its Alloys: A Review".** Journal of Materials Processing Technology, Vol. 173, No. 2, pp. 125-135, 2006.

[33] Liu, Y., et al., **"Experimental Investigation on Form Error for Slow Tool Servo Diamond Turning of Micro Lens Arrays on the Roller Mold".** Materials, Vol. 11, No. 10, pp. 1816, 2018.
[34] Venkatesan, K., R. Ramanujam, and P. Kuppan, **"Laser Assisted Machining of Difficult to Cut Materials: Research Opportunities and Future Directions-A Comprehensive Review".** Procedia Engineering, Vol. 97, pp. 1626-1636, 2014.
[35] Samant, A.N. and N.B. Dahotre, **"Laser Machining of Structural Ceramics—A Review".** Journal of the European ceramic society, Vol. 29, No. 6, pp. 969-993, 2009.
[36] Sofuoğlu, M.A., et al., **"Experimental Investigation of Machining Characteristics and Chatter Stability for Hastelloy-X with Ultrasonic and Hot Turning".** The International Journal of Advanced Manufacturing Technology, Vol. 95, , No. 1-4, pp. 83-97, 2018.
[37] Huang, S., et al., **"Diamond-cutting Ferrous Metals Assisted by Cold Plasma and Ultrasonic Elliptical Vibration".** The International Journal of Advanced Manufacturing Technology, Vol. 85, No. 1-4, pp. 673-681, 2016.
[38] Xu, W., et al., **"Diamond Wear Properties in Cold Plasma Jet".** Diamond and Related Materials, Vol. 48, pp. 96-103, 2014.
[39] Yip, W. and S. To, **"Effects of Magnetic Field on Microstructures and Mechanical Properties of Titanium Alloys in Ultra-precision Diamond Turning".** *Materials Research Express*, Vol. 6, No. 5, pp. 056553, 2019.
[40] Yip, W. and S. To, **"Reduction of Material Swelling and Recovery of Titanium Alloys in Diamond Cutting by Magnetic Field Assistance".** *Journal of Alloys and Compounds*, Vol. 722, pp. 525-531, 2017.
[41] Yip, W. and S. To, **"Tool Life Enhancement in Dry Diamond Turning of Titanium Alloys Using an Eddy Current Damping and a Magnetic Field For Sustainable Manufacturing".** *Journal of Cleaner Production*, Vol. 168, pp. 929-939, 2017.
[42] Hatefi, S. and K. Abou-El-Hossein, **"Feasibility Study on Design and Development of a Hybrid Controller for Ultra-Precision Single-Point Diamond Turning".** *Majlesi Journal of Electrical Engineering*, Vol. 13, No. 2, pp. 121-128, 2019.
[43] Hatefi, S., O. Ghahraei, and B. Bahraminejad, **"Design and Development of a Novel Multi-Axis Automatic Controller for Improving Accuracy in CNC Applications".** *Majlesi Journal of Electrical Engineering*, Vol. 11, No. 1, pp. 19, 2017.
[44] Hatefi, S., et al., **"Continuous Distraction Osteogenesis Device with MAAC Controller For Mandibular Reconstruction Applications".** *BioMedical Engineering OnLine*, Vol. 18, No. 1, pp. 43, 2019.