Feasibility Study on Design and Development of a Hybrid Controller for Ultra-Precision Single-Point Diamond Turning

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ABSTRACT:
The recent realm and leader technology in advanced manufacturing of critical components, and optical surfaces is ultra-precision Single-Point Diamond Turning (SPDT). This state-of-the-art technology enables machining optical surfaces with nanometric accuracies and surface roughness from order of nanometers. However, there are drawbacks in this process and SPDT is limited when machining brittle- and difficult-to-cut materials. Non-conventional assisted technologies have been developed and used to assist SPDT for extending turning limitations. Recently, application of novel hybrid platforms for SPDT has been emerging to achieve the best possible outcome in optical surface generation. Hybrid controllers are playing the main role in a hybrid platform. Main tasks of a hybrid controller in a hybrid SPDT platform include; real-time assisted technologies performance control, setting working parameters, and effective communication with implemented sensors for on-machine metrology. Hybrid processes in SPDT are recently emerging and there have been a few studies on designing and developing such novel platforms for SPDT. The purpose of this study is to design and simulate a Multi-Axis Automatic Hybrid Controller (MAAHC) to be used in a hybrid platform for assisting SPDT technologies. MAAHC has three process cores which work independently and communicate simultaneously. The designed MAAHC has different capabilities; MAAHC can control and drive ultrasonic vibration system, laser beam system, cold plasma system, and on-machine metrology systems i.e. vibration and force sensors. In addition, MAAHC is capable to control and drive two stepper motors in two independent linear axes. Electronic switches, communication ports, and high-performance switching have provided a full control on secondary technologies assisting in realizing a hybrid SPDT platform. Theoretical equations, design specifications, and simulation results have revealed that the proposed MAAHC is functional and has met all requirements to control such a hybrid SPDT process.

KEYWORDS: Hybrid Controller, Ultra-Precision Machining, Single-Point Diamond Turning.

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1. INTRODUCTION

Advanced Manufacturing (AM) is the process of using advanced methods for generating critical components. Previously, precision machining enabled manufacturing components with precise surface characteristics having less than one millimeter geometry. In precision machining, the sharpness of cutting tool is in the order of micrometers. Precision machining has been widely studied and various machines, controllers, machine-tool, and metrology systems for micro-machining have been developed and successfully used. However, there are other various complications that have limited the precision machining [1-3]. In AM, machining processes including turning, drilling, grinding, and milling, require high levels of surface smoothness and dimensional accuracy. Recently, cutting-edge research and Nano-technology have demanded manufacturing optical surfaces with nanometric characteristics. Therefore, there has been a necessity to go beyond classic precision machining practices for enabling manufacturing of products with higher quality and optical levels of smoothness [4-7].

By using state-of-the-art technology and implementing novel controlling methods, next generation of machines, called ultra-precision machinery, have been developed, and used. Ultra-Precision Machining (UPM) has enabled generating critical products and optical surfaces with nanometric characteristics and high levels of smoothness [8-10]. UPM has found a wide range of application in various industry sectors including space science, biomedical, automotive, defense, dental, electronics, computer, and entertainment. Single-Point Diamond Turning (SPDT) technology is the most favor, and leader technology in UPM. Fig. 1 illustrates the standard structure of a SPDT machine. As a result of the development of new machine-tool design, nanometric controllers, computer numerical control (CNC) technology, high-speed algorithms, vibration free platform, and accurate tool holder, SPDT evolved rapidly. In SPDT, a prescribed single-crystalline diamond is used as the cutting tool which penetrates the workpiece surface and cut it at the micrometric level [11-14].

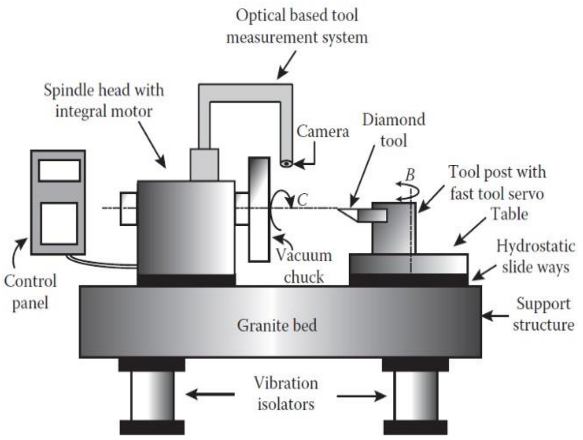

Fig. 1. Standard structure of single-point diamond turning machine [2].

However, different factors influence surface generation and limit surface smoothness in SPDT. There have been unsolved drawbacks and limitations in this technology. These limitations are more serious when turning brittle- and difficult-to-cut materials such as optical silicon and germanium. Various efforts have been undertaken to extend limitations, reduce destructive effects, and optimize turning condition [15-17]. Non-conventional and modern technologies have been used in SPDT to assist the process from different perspectives including, thermal, physical, chemical, and mechanical. Assisted-SPDT have enabled turning of brittle- and difficult-to-cut materials. In addition, they could significantly improve machining condition and process parameters. There are various techniques which have been used in assisted-SPDT. These include active mechanical vibration, hot machining, magnetic field, ion-implantation, and cold plasma jet. Although assisted technologies could provide a better machining condition, constructively impact the process, and improve surface quality, limitations are not completely and satisfactorily solved, especially in turning difficult-to-cut materials. In addition, non-conventional assisted technologies could have destructive effects on turning process and limit the process capabilities. High tool wear, shorter diamond tool life, and low quality in surface generation are some of these major limitations [18-25].

On the other hand, on-machine metrology for measuring, testing, and diagnosing while turning is an important key. By implementing an automatic controller, sensors, and measurement equipment, online procedures for testing and correcting machining parameters can be realized. A few precise sensors and measurement systems with nanometric accuracies have been designed, developed, and implemented in SPDT process for enabling on-machine metrology and improving machining conditions via setting optimized parameters. Laser-based optical measurement system has been implemented for machine-tool and work piece vibration measurement. Electromagnetic hall sensing has been implemented for measuring vibration amplitude and generated magnetic field [2, 8, 24-29].

The above-mentioned assisted technologies and metrology systems could be implemented simultaneously to greatly affect SPDT process. Combining the non-conventional machining processes with the traditional mechanical machining processes in the same machine platform would result in a hybrid machining platform, where, two or more machining processes are implemented independently, controlled simultaneously, and interacted at the same zone to significantly improve the performance of the machining process. In a hybrid platform, different elements could be implemented, these include hybrid machine, hybrid tooling, on-machine metrology system, work handling system, and process modeling. Recently, hybrid platforms for SPDT have been introduced and developed. In hybrid-SPDT solutions, turning process benefits from different perspectives. In addition, on-machine metrology systems could be implemented in hybrid-SPDT platform [13], [28], [30], [31].

This study aims to design a novel automatic controller for using in a hybrid SPDT platform for controlling, reconfiguring, and using implemented non-conventional technologies, metrology systems, and available data. In the proposed controller, three microcontrollers are used to provide a real-time control, scan, and system configuration. This triple-core controller is able to control the functionality and process parameters of ultrasonic vibration, laser beam, and cold plasma assisting technologies. By providing a two-axes linear controller, MAAHC can realize a positioning controlling of external magnetic field in the presence of an assisting magnetic field. In addition, MAAHC has the capability to connect to various analog and digital sensors, and read data. Therefore, on-machine metrology is possible during SPDT. After the theory and design of the proposed MAAHC, simulation results are presented to validate the feasibility of designed controller, to assess the performance of the designed system, and to identify key challenges that need to be addressed in further development of the system.

2. DESIGN OF HYBRYD CONTROLLER

The design of MAAHC consists of three connected control units to provide an accurate control while operating assisted technologies in the hybrid SPDT platform; each technique is controlled independently with high-speed and accurate automatic procedures. The block diagram and working principles of the designed MAAHC are illustrated in Fig. 2. In the designed block diagram, main control unit is colored in yellow, and the two assisting units are colored in green and blue. Design of MAAHC consists of following units; power supply, controller, display and control-pad, and switching ports. In the design of power source unit, 5 and 12 (V) are voltage rates that is considered in designing MAAHC; for providing necessary power for running different processes, a DC power supply, MAISHENG switching regulated supply, with output voltage 0-15 (V) and current 20 (A) is used.

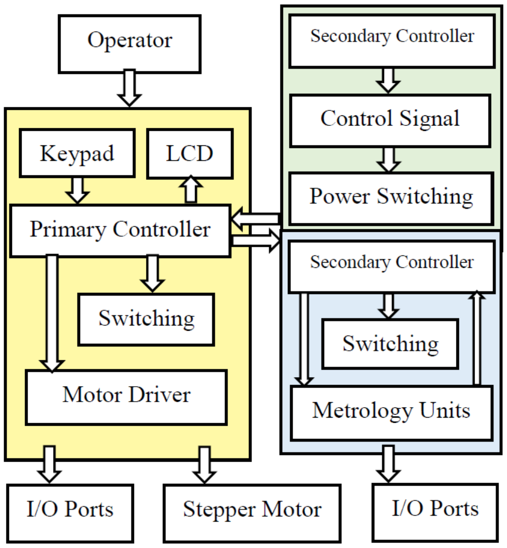

Fig. 2. Block diagram of MAAHC.

2.1. Control units

In the design of MAAHC, three high-performance microcontrollers are implemented. There is a main control unit which will control the whole processes and communicate with all units. A high-performance, low-power microchip 8-bit AVR RIS-based microcontroller, ATmega32A, is used as the primary controller. In a hybrid platform, based on the designed system and implemented techniques, linear movements could be included. Therefore, a hybrid controller needs to have the capability of controlling linear movements and precisely drive stepper motors. In MAAHC, the primary controller has the capability of controlling two independent linear movements. By using a linear controlling method, MAAC, accurate positioning in a linear axis have been enabled; MAAC has been used in Computer Numerical Control (CNC) machinery and linear systems for controlling axial movements. In the driver unit, two L298 dual full-bridge motor drivers are implemented for executing linear movements and driving stepper motors. The output control signals of the primary controller are connected to the motor drivers while driving the motors with an open-loop control system. In the design of the hybrid system, NEMA 17 hybrid stepper motor is used. Specifications of this stepper motor are given in Table 1. In addition, a human-machine interface is designed; this includes a liquid crystal panel for showing process parameters, and a keypad for communicating and configuring MAAHC.

Table 1. The stepper motor specifications.

NEMA 17 stepper motor	
Step Angle	1.8 degree
Rated voltage	12 VDC
Number of Phase	4
Current	400 mA
DC Resistance	30 Ω
Phase inductance	37 mH
Holding Torque	2600 g/cm
Rotor Inertia	34 g/cm^3

In addition to primary controller, two other high-performance microcontrollers are implemented as secondary controllers; to accurately and independently control sensitive processes implemented. In a hybrid SPDT platform, implementing active vibration assistance technique would be a prioritized choice. For this purpose, MAAHC has the capability to operate an ultrasonic-vibration assistance system. First assisted unit in MAAHC is used for controlling such a vibration generation process. In this unit, a high-performance, low-power microchip 8-bit AVR RIS-based microcontroller, ATmega32A is used. Specifications of this microcontroller would enable generating control signals with the desired frequency, while switching vibration system's high-voltage switches with desired frequency for executing the active vibration. In addition, two I/O channels are used as the electronic switches for switching the power of system. Laser beam assistance could be implemented in the hybrid SPDT platform as an effective technique. MAAHC is able to operate this system and control the laser emitter and its operational parameters. Second assisted control unit in MAAHC is designed and implemented for controlling laser machining process; a high-performance, low-power microchip 8-bit AVR RIS-based microcontroller, ATmega32A is used in this unit. Two I/O channels are used as electronic switches for switching the power of laser assisting system. In addition, a controllable PWM output with adjustable duty cycle is included in the design to control the emitting power of laser. This unit could also control the process of cold plasma jet system. For controlling this, a system two parameters should be considered; a digital I/O port for controlling and switching the power source, and two other digital I/O ports for controlling the gas flow via electric valve. Beside controlling various assisting technologies, in a hybrid SPDT platform, different on-machine measurement systems and sensors could be designed and implemented during SPDT. This unit will enable communication between MAAHC and on-machine metrology systems. MAAHC is able to read data from different sensors and determine the machining parameters. This information could be used in auto-tuning of implemented techniques i.e. determining and setting the resonance frequency for the ultrasonic vibration system and tuning the generated frequency. In another subsequent, primary controller communicates with units and metrology systems, receives available data, and displays machining parameters and turning conditions on MAAHC's display. The designed circuit of MAAHC is illustrated in Fig. 3.

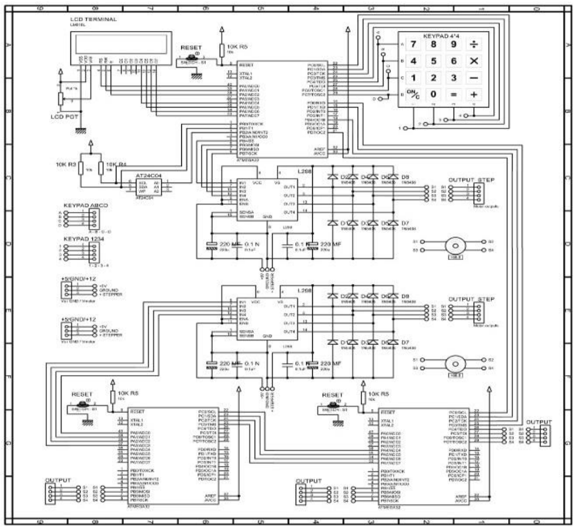

Fig. 3. The designed circuit of MAAHC.

2.2. Modeling and Simulation

MAAHC has the capability to control and drive stepper motors in three working states; full- step, half-step, and micro-step. To achieve an optimized linear motion, micro-stepping mode is selected to drive stepper motors while enabling the maximum positioning accuracy, and providing more stability and resolution compared to other driving methods. Using micro-stepping, driving mode would also eliminate resonance and low speed ripple effects and improves the quality of movements. The mathematical equation, known as differential equations, based on the working principles of a hybrid stepper motor are given below. In the equations mentioned, i_a and v_a are voltage and current of phase A, respectively, i_b and v_b are voltage and current of phase B of the motor. ω is rotor's rotational speed, θ is the rotor's angular position, and T is load torque. Other parameters including magnetic coupling, detent torque, and unstable inductance are neglected in the design and implementing model; and simulation.

$$\frac{dia}{dt} = \frac{va+km.\omega.sin(N.\theta)-Ria}{L} \tag{1}$$

$$\frac{dib}{dt} = \frac{vb+Km.\omega.cos(N.\theta)-Ria}{L} \tag{2}$$

$$\frac{d\omega}{dt} = \frac{Km.ib.cos(N.\theta)-T-Km.ia.sin(N.\theta)-Kv.\omega}{J} \tag{3}$$

$$\frac{d\theta}{dt} = \omega \tag{4}$$

Modeling and simulation of stepper motor and MAAHC is performed using MATLAB-SIMULINK for evaluating the designed system and selected controlling methods. The overall design of the simulation model is illustrated in Fig. 4. The designed subsystem of position and speed is shown in Fig. 5.

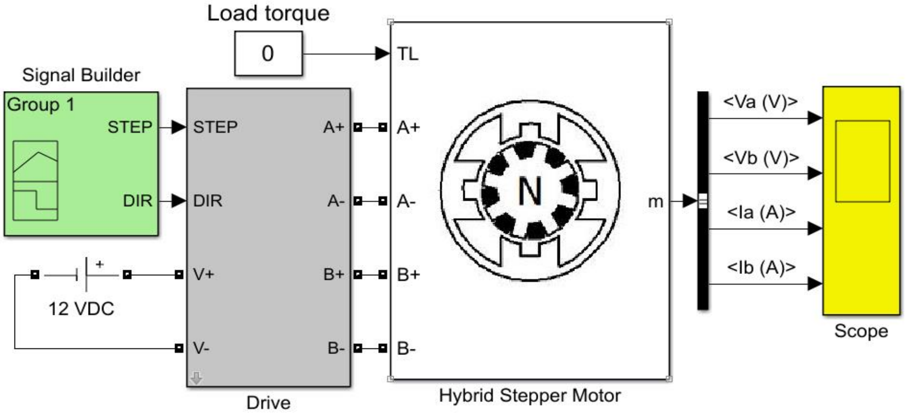

Fig. 4. Overall design of the model.

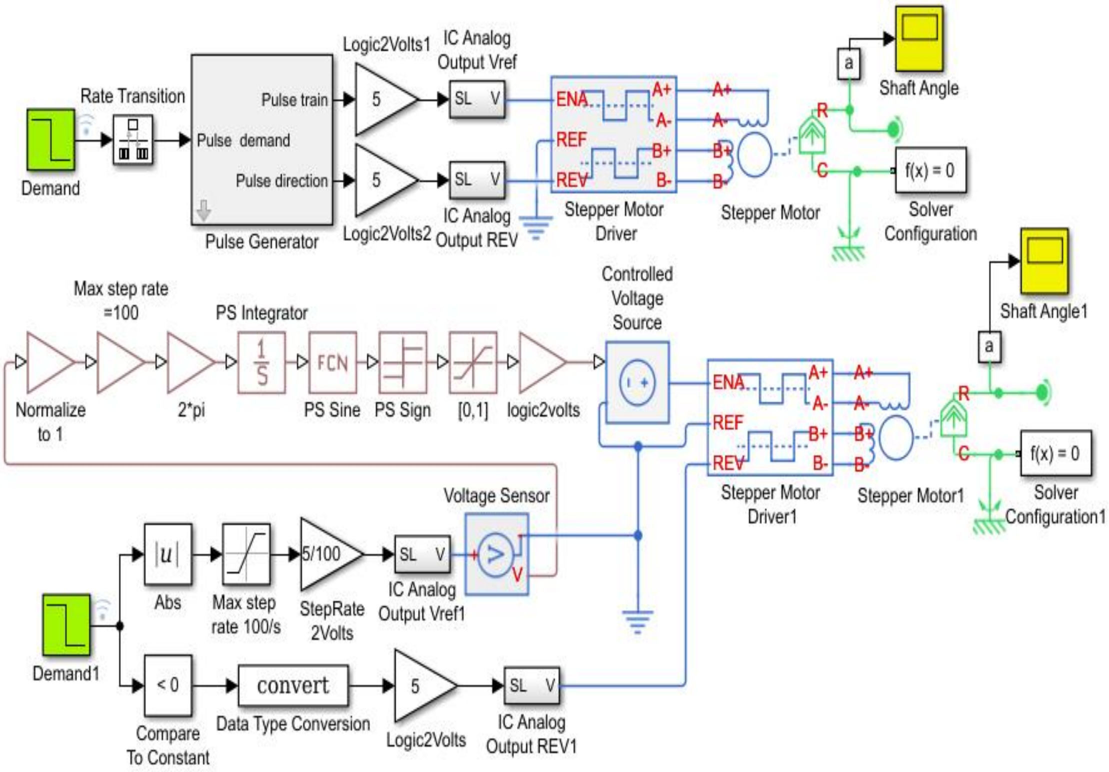

Fig. 5. Speed and position subsystems.

3. RESULTS

The designed MAAHC has the capability to drive the stepper motor in micro stepping mode while controlling linear movement with an open-loop control system. After the necessary parameters of the selected components are defined and set in models, the simulation is run. The execution time for the simulation process is defined as 0.1 second. Fig. 6 shows the detailed waveforms voltage and current in stepper motor phases. V_a shows the voltage waveform in phase A, I_a shows the current waveform of phase A. V_b shows the voltage waveform in phase B, and I_b shows the current waveform in phase B. The motor's shaft position and rotational speed are shown in Fig. 7. In addition, the simulation results of the signal generator unit, for controlling and switching ultrasonic vibration system, show that MAAHC has the capability of generating switching control signals with various frequency values. In the simulation process, parameters are set to generate three high-frequency switching control signals; 15 KHz, 35 KHz, and 70 KHz. Fig. 8 illustrated the simulation results of switching port.

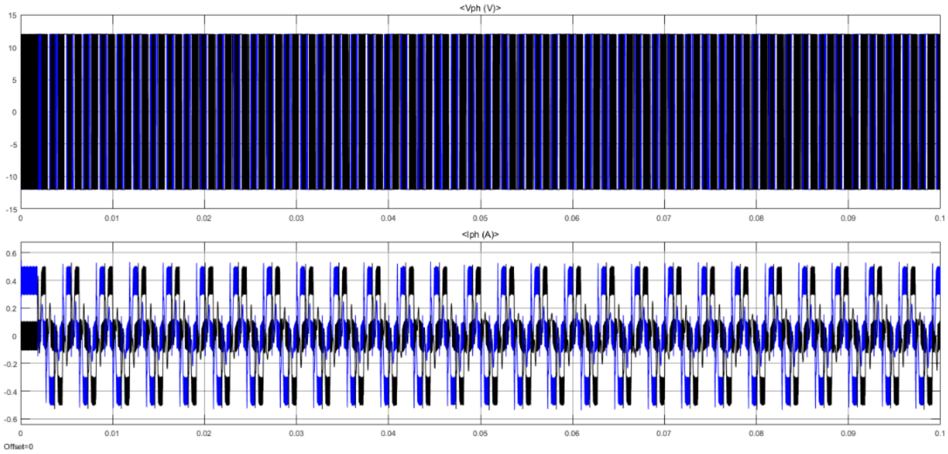

Fig. 6. Simulation results: voltages and currents of phases in stepper motor.

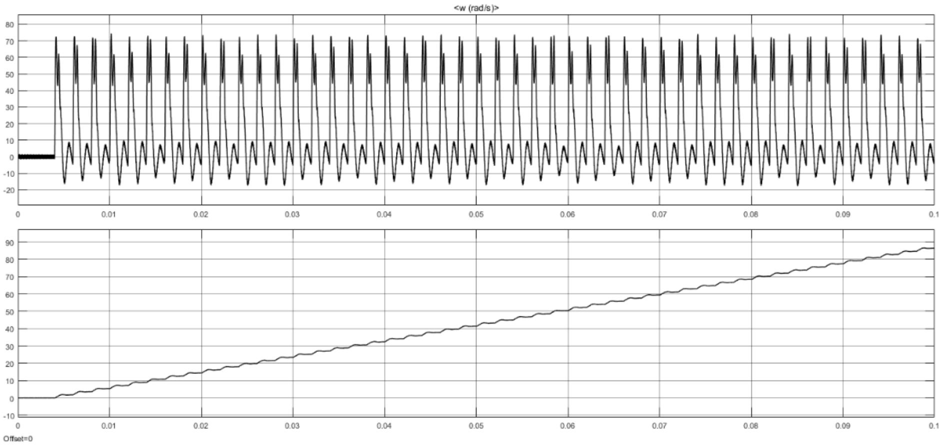

Fig. 7. Simulation results: Shaft’s rotational speed and position.

Fig. 8. Simulation results of switching in signal generator unit.

4. DISCUSSION

In advanced machining methods, SPDT technology for manufacturing optical surfaces has emerged rapidly; cutting surfaces with nanometric specifications and very low surface roughness is the brilliant outcome of this technique. In a SPDT platform, non-conventional assisted machining techniques have been implemented to impact the workpiece surface while turning, and consequently improve the machining parameters. Recently, the application of hybrid SPDT has been getting more attention. A few hybrid SPDT platforms have been developed and implemented. However, more research and investigations need to be conducted to enable a high-performance hybrid machining process. One of main challenges in a hybrid SPDT procedure is to automatically control the whole processes and technologies which are simultaneously and independently performing. Another challenge is to measure machining conditions through on-machine metrology systems, and to tune the controlling parameters in real-time. The objective of this study is to design a hybrid controller for operating a hybrid SPDT machining process, while controlling the added assisting technologies and enabling a smooth and accurate linear movement in two linear axes. The proposed MAAHC could drive stepper motors in the micro-stepping drive mode. Controlling the linear movement with MAAC control method can provide a smooth and accurate positioning. Previous studies have demonstrated the functionality of such linear control method [32-35]. In micro-stepping drive method, stator flux moves in a more continuous way and provides a precise and smooth control of the motor’s shaft position. Using such controlling method reduces unwanted vibrations and noise while driving the axial motion [36-40]. Simulation results have shown that between the two phases of stepper motor, voltage waveforms are 90 degree displaced, also, current waveforms are similar to sine and cosine waveforms, and are 90 degree displaced as well. Therefore, the results of simulations are in agreement with the theoretical equations and calculations. Simulations results have shown that the MAAHC could generate high-frequency signals and could enable controlling and switching a vibration system with a wide range of frequencies. MAAHC is equipped with a human-machine interface for enabling setting operation parameters. A crystal liquid display and a keypad are implemented with MAAHC for programming, debugging, and setting operation parameters. This feature would allow the user to set various machining parameters, and check or modify them during the procedure. In the design of MAAHC, a serial eeprom memory is implemented with primary controller to provide a real-time backup system for all running processes. In case there is a failure in any process, process data, working parameters, and machining conditions could be recovered and used.

5. CONCLUSION

In this study, a novel controller, MAAHC, is designed and simulated to be used in hybrid SPDT platform for enabling operating and controlling hybrid processes automatically, precisely, and independently. In a hybrid platform in SPDT, various machining techniques could be implemented and used simultaneously to standard SPDT process to improve turning procedure in terms of different aspects. In the designed MAAHC, three independent high-performance microcontrollers are implemented to enable best controlling condition with high resolution and accuracy. In a hybrid SPDT platform, MAAHC has the capability to fully control and operate possibly implemented non-conventional assisting technologies. It has the ability to set, modify, and tune the machining parameters of each assisting technique. MAAHC could generate adjustable high-frequency signal for executing high-frequency switching to operate and control an ultrasonic vibration system. MAAHC has also the capability to operate and control a laser beam and cold plasma jet systems. The designed system shows it has the ability to control and drive two smooth and accurate linear movements by implementing a motor driver unit. By programming and using I/O ports of MAAHC, different functions and operations could be controlled. In addition, MAAHC is able to get connected to on-machine metrology systems, receive data, and improve turning conditions by a real-time tuning of the machining parameters. To justify the functionality of the designed MAAHC, a set of modeling and simulations have been implemented. The analyses have been carried out, and results have been investigated. Result of performed studies have revealed that the designed MAAHC is functional and has met all necessary requirements for a successful hybrid SPDT procedure.

6. FUTURE WORKS

Hybrid SPDT is a novel ultra-precision machining solution. Only a few studies have been performed for studying the effect of hybrid processes on a SPDT platform. Therefore, more investigation needs to be undertaken to study the effects of addition of hybrid processes from various aspects. The designed MAAHC could be implemented in a hybrid SPDT procedure for providing a fully automatic process control while operating assisted technologies. The designed system has met necessary requirements for controlling a hybrid process with sufficient accuracy and stability. Thus, the next step could be the development of such MAAHC controller for implementing in hybrid SPDT process. In addition, more development on on-machine metrology systems needs to be done; implementing measurement system could measure the performance of machining parameters while providing this data to be used in MAAHC.

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