

Towards Computer Vision Feedback for Enhanced CNC Machining

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Abstract—A vision-based sensing utility is proposed and developed to enhance the performance of CNC milling machines. Two cameras are attached to the machine spindle to provide visual information on work-piece surface quality while machining. This information is processed and processing outcome is used to improve the surface roughness of the machined part by adjusting the employed machining parameters. To facilitate on-line monitoring and control, computer programs are developed to manipulate the source G-code file in order to enable real time integration of the gained feedback information. The manipulated G-code program is then executed by the machine controller to allow adaptive control of the work-piece machining. The developed system automatically determines which camera is required to provide scene data for each step of tool path movement. Relative camera is then activated just as the machine completes the cutting of each tool path segment. Acquired vision data is processed to evaluate resulting surface roughness and accordingly a decision is made to either maintain the implied machining parameters or adjust their values to beneficially suit the machining task and result in better surface quality. The developed approach is tested and verified experimentally. Promising results are acquired that encourage further development towards full integration of CNC-vision systems.

Keywords—CNC-vision; computer vision control; CNC machining

I. INTRODUCTION

Automation of manufacturing systems is a main demand of industry. The aim is to reduce the operating cost and improve product quality [1]. Work-piece surface roughness and tool condition could play an important role in the assessment process of automated manufacturing performance. In addition surface roughness and tool condition influence the product manufacturing quality. The monitoring and control of these issues could be considered as a crucial topic in automated manufacturing.

The pioneer research to integrate CNC machines with vision systems is presented in [1]. More recent literatures on machine tool deal with cutting tool monitoring. In general, conducted researches are concerned with the use of monitoring sensors and analysing the acquired data to predict

cutting tool condition. Several studies are conducted to monitor tool and machine using single sensor as in [2-4]. These studies have proposed and examined proposed techniques for sensor data analysis. The fusion of data acquired from several sensors is also given considerable attention in recent published works e.g. [5- 7].

Recent advances in the field of image processing have led the way to the development of various in cycle vision sensors that can provide direct and indirect estimate of the tool condition and work-piece monitoring [8]. Several researches are carried out in tool condition monitoring using vision system as in [9-10]. However, less attention was given to the development of feedback systems using vision data to improve CNC machines performance.

In this article, an approach for CNC machine monitoring and control based on vision data acquired from two alternating cameras is proposed and verified experimentally on a CNC machine. The proposed approach starts by segmenting the machining instructions in the Source G-code Program (SGP) to pre-defined small incremental movements and incorporate several control statement blocks. A New Generated G-code Program (NGGP) is therefore automatically produced to substitute the SGP. At this processing stage, the exact and overall tool paths as well as implied machining parameters and other miscellaneous functions are kept without alteration in the NGGP. However, the modification made in the NGGP aims to segment the tool path as well as to add several codes to facilitate adaptive control using vision-based feedback, hence processing results of vision data will consequently adjusts the implied machining parameters in a closed-loop system setup.

II. OVERVIEW OF THE DEVELOPED SYSTEM

The proposed and developed system aims to evaluate and control machining performance of CNC machines by vision-based monitoring and assessment of resulting surface roughness. In order to introduce vision-based roughness measurement technique to CNC machines a number of scientific as well as technical issues needs to be overcome including scene visibility issue, coolant and cut chips obstructing the visual scene, camera mounting, lighting,

effects of machine vibration on the quality of obtained roughness measurement, selection of a roughness parameter to be employed, and machining parameters effects on acquired roughness measurement. Hence all these issues were considered and dealt with in the developed system.

The proposed system includes several processing stages to facilitate the achievement of its goal. The first processing stage aims to identify the most recent machined area to enable its processing, therefore outcome from processing and evaluation of its surface roughness will drive the decision making on the values of machining parameters that should be employed in the next step of work-piece machining. The proposed method to achieve such task consists of several comparators and control blocks organized sequentially to achieve comprehensive visual feedback system. The implied processing methodology utilizes the machining parameters recorded within the SGP, hence these values are considered as a comparison base and their values are adjusted or modified according to a decision making task that is based on the processing of the incoming signal from the vision system. The adjusted or modified machining parameters values are then recorded in the output files of the NGGP. Consequently, these updated values are called and loaded to the machine controller in an automatic way; hence next segment machining is carried out accordingly.

Fig. 1 shows a block diagram of the proposed and developed system. The process starts off-line just before the actual machining take place. The system reads and processes the SGP to segment the machining path into small steps of predefined length that is suitable for roughness evaluation. The aim is to allow instantaneous and sequential assessment of machining performance. Control blocks are also generated and added as separate programming coded blocks post each machining segment within the NGGP. The output from this stage is a set of chained G-code subroutines.

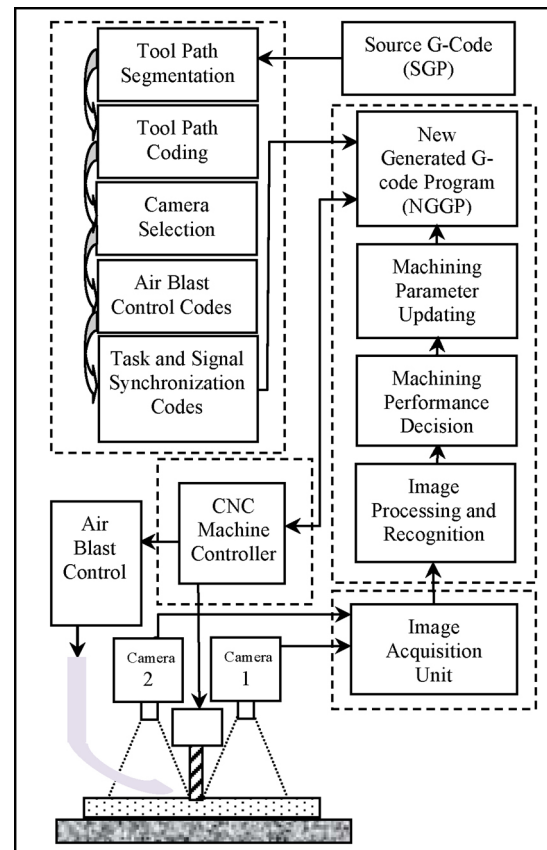


Figure 1. Block diagram of the proposed control and monitoring system.

The system includes a vision system of two cameras which is mounted on the machine spindle to allow instantaneous monitoring of the work-piece surface roughness. The acquired images from the vision system are analysed and resulting vision based surface roughness are sent to the developed machining performance decision algorithm where a decision on whether to alter or keep the current machining parameters is taken. If altered, the new values of the machining parameters are recorded in the corresponding sub G-code program that is called by the NGGP using a proper instructional block. The machining performance decision employ a comparison between acquired vision-based work piece surface roughness and expected values of surface roughness resulting from the application using employed machining parameters.

The control tasks of the developed system are discussed in the next section.

III. MACHINE CONTROL AND IMAGE ACQUISITION

The main control tasks implemented in the developed system include tool path segmentation, clearing out the camera field of view from cut-chips, camera activation to provide valid scene of the most recent machined area, synchronising and automatic control of applied tasks. In this section, a brief discussion is given on each of the main control tasks implemented in the developed system.

A. Tool Path Segmentation:

In order to assess the performance of the machining quality, roughness of most recently machined surface is monitored. Therefore, to enable dynamic monitoring process be imposed, each machining block of the SGP is needed to be divided into group of segmented blocks, where each segmented block presents a predefined portion of the total tool path entity. The type of the tool path entity (i.e. whether a linear or circular interpolation movement) for each segment is kept the same as in the original SGP), whereas the length of this entity is set to a selected value ($\vec{S}_m$) that is suitable to undergo surface roughness evaluation in a dynamic on-line application.

Usually, the machining blocks in G-coded programs include G01 for linear interpolation and G02 & G03 for circular interpolation. Within X-Y plane, the linear interpolation of a line having ($\vec{S}$) units of length will yield three possible types of the movement directions. The first and second movement directions are associated with linear movements either along X or along Y axis. Whereas the third type of movement involves linear movement in both X and Y axes instantaneously. The path segmentation process for G01 is developed to handle all three cases of linear movement so that the resulting segmented path will include n number of segments where each segment is of a movement length equal to the pre-selected value of (V). The exceptional case is the last segment of the entity $\vec{S}_e$ which will have a non zero value if $\frac{\|\vec{S}\|}{V}$ does not yield integer value. In this case the last segment will have shorter length and will be discarded from the surface roughness monitoring process. Hence the summation of all segment lengths is equal to $\vec{S}$:

$$\vec{S} = \left(\sum_{i=1}^{n-1} \vec{S}_m(i) \right) + \vec{S}_e \quad (1)$$

In the case of circular interpolation, the arc perimeter is also segmented by the developed algorithm into n number of arc segments of V length. Each arc segment will maintain its movement direction relative to either clockwise or counter clockwise rotational direction (G02 or G03). The last segment of the arc follows the same principle of the already discussed line entity. Fig. 2 shows a segmented arc, where the last segment ($\vec{S}_e$) is discarded by the developed surface roughness monitoring process as it may not provide enough length.

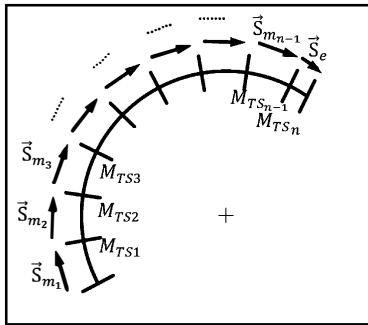


Figure 2. Developed arc segmentation process.

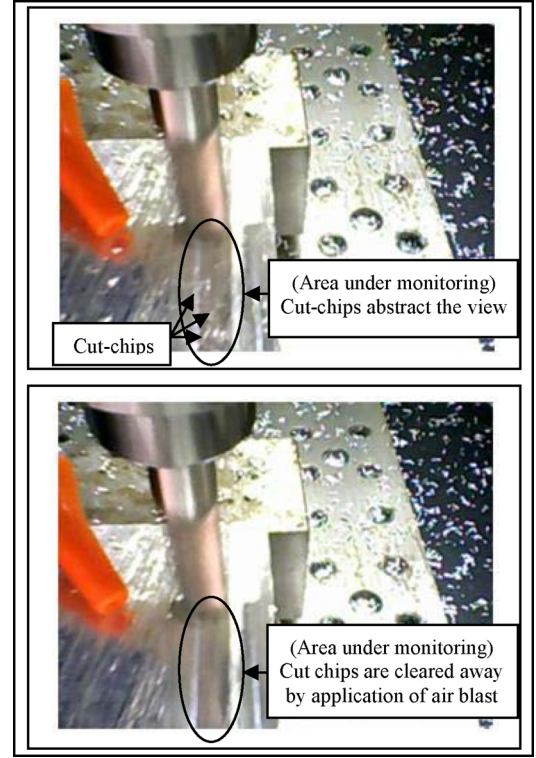


Figure 3. The effect of air blast on the machined area.

The machining time M_{TE} for any entity machining as programmed in the SGP can be calculated by:

$$M_{TE} = \frac{\|\vec{S}\|}{F} \quad (2)$$

where F is the programmed feed rate value (mm/min). However the time required for the machining and processing of the complete segments set of the same entity (T_{MP}) can be calculated as:

$$T_{MP} = \sum_{k=1}^n M_{TS}(k) + \sum_{q=1}^{n-1} T_{PS}(q) \quad (3)$$

where $M_{TS}(k)$ is the required time for the machining of segment k in the NGGP and T_{PS} is the time to process the acquired image and update the machining parameters in the NGGP.

In order to beneficially apply the developed system in real applications the time required for the machining of any tool path entity in the NGGP must be less than the time required for machining the same entity of the tool path based on the SGP:

$$T_{MP} < M_{TE} \quad (4)$$

In order to comply with Equation (4) image processing time should be kept as minimum as possible. In addition, employed feed rate should be increased though quality of acquired surface should be maintained to match design requirement. This can only be achieved by dynamically and on-line monitoring of resulting surface roughness to adaptively control the cutting process.

B. Clearing Out the Camera Field of View From Cut-Chips:

In order to acquire reliable image data the camera field of view should be clear from cut-chips so that only machined surface be visible in the image scene. In addition, if coolant is used then it will also add complication to the scene. To overcome such limitation the developed system employs an air-blast sub-system to serve as an alternative to the usual liquid coolant. Nevertheless the air blast will also serve to clear out the field of view from cut-chips. However to avoid any image noise resulting from the air blast system, a turn off signal of the air blast system is coded in the NGGP after each machining of tool path segment just before the image acquisition starts so that the camera can acquire quality image of the surface without being affected by cut-chips. Once the image is acquired the air blast system is turned on again by the CNC controller via the execution of an extra coded signal within the NGGP. This approach is applied experimentally to verify its validity. Superb and positive results are acquired hence demonstrate the validity of the proposed technique, Fig 3. However the effect of using air blast instead of coolant on tool life is left for future investigation.

C. Activation of Relative Camera to Provide Valid Scene of the Most Recent Machined Area:

In milling operations the movement of the tool in the different directions will definitely obstructs the machined surface from being captured by image acquisition using single camera. Therefore two cameras are used and mounted on machine spindle sides to enable the acquisition of the most recent machined surface segment, Fig. 4. Hence a procedure is developed to decide which camera is used for each case of applied movements. Fig. 5 shows the relationship of the camera setup with the CNC machine axes. In order to activate the correct camera the developed procedure checks the machining direction of the most recent conducted machining. In the cases of path movements towards +X, +Y, +X & +Y, or +X & -Y directions, Camera 1 is activated and a single image frame is recorded, otherwise Camera 2 is activated.

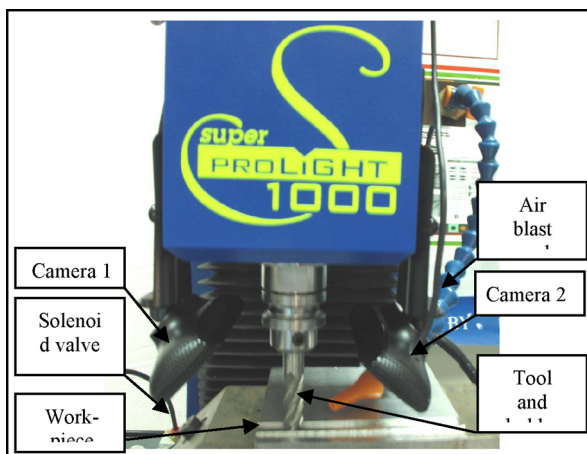


Figure 4. Super-prolight-1000 machine spindle with mounted cameras.

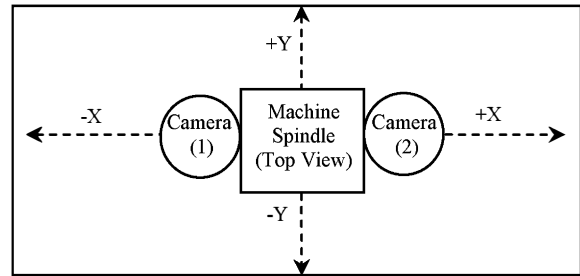


Figure 5. Cameras setup.

D. Synchronization and Automatic Control of Applied Tasks:

The developed system includes several hardware modules that are interfaced and integrated to achieve the goal. The automatic control of these modules to enable them work systematically is achieved by activation/deactivation and synchronization signals sent and received by the system modules. Fig. 6 provides a schematic diagram of developed modules interfacing and the synchronizing. The system follows the following sequence:

- The host computer processes the SGP and produces the NGGP that includes segmented tool path arranged in a set of chained programs.
- The CNC machine controller loads and executes the first program of the NGGP (task 1). On the same time the host computer determine the direction of tool path movement in order to decide which camera will be activated in a later stage.
- Air blast is turned on via solenoid activation signal (task 2a) and cutting is then start according to the programmed tool path (task 2b).
- Once executed, a deactivation signal is sent to the air blast solenoid (task 3).
- A signal is sent to the host computer to acknowledge that the system is ready to acquire a snap-shot of the machined surface (task 4).
- The host computer activates and controls relative camera to acquire and store the required image (task 5a&5b).
- The host computer processes acquires the image data and determines resulting surface roughness. Decision is then taken on whether to alter/adjust the applied machining parameters or keep the current values of these parameters. If altered, the host computer edits the next chain-program of the NGGP to include the new values of the machining parameters.
- The host computer sends a signal out to the CNC machine controller to acknowledge that the processes is completed and the next sub-program of the NGGP is ready to be loaded and executed (task 6).

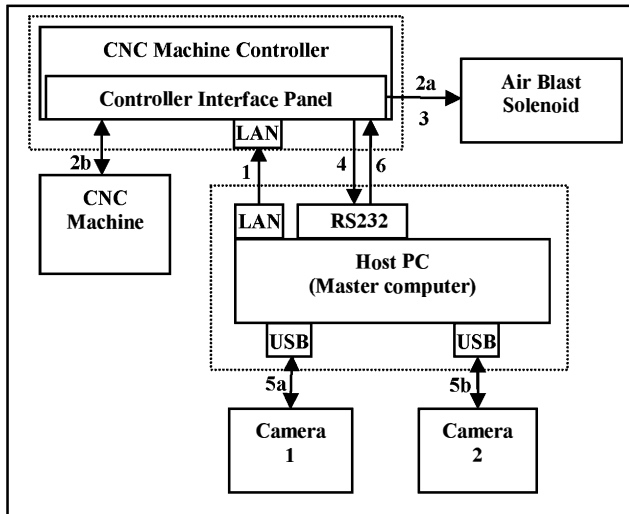


Figure 6. Developed system communication and tasks synchronizing

IV. VISION BASED SURFACE ROUGHNESS EVALUATION

Vision based roughness measurement is not a straight forward task. Development of a reliable methodology requires much attention to successfully provide on-line roughness results in real time. Although a number of published articles assure that vision data provide valid information regarding surface roughness, this task requires further investigation to suit the environment of each of the developed system.

Experimental investigation is carried out by the authors of this article to analyse more than sixty specimens that were machined according to selected machining parameters. Each of these specimens were undergone a detailed roughness measurement using SE1200 Kosaka stylus-based instrument. Results were acquired as roughness parameters values as well as raw profile data. The aim is to develop a general model for the machining-roughness relationship based on the adopted machining parameters and conditions.

Visual images of the 60 specimens were also acquired and processed to extract relative roughness data. Fig. 7 provides examples of acquired images of the machined specimens' surfaces. The Figure also provides pixel intensities across a single line of the same images. It could be noted from the intensity graphs that although roughness information are inherited by vision data, the image data should undergo several processing to extract roughness measurement from them. The authors have adopted the methodology presented in [11] to process vision data, however, more investigation are still needed before reporting final findings.

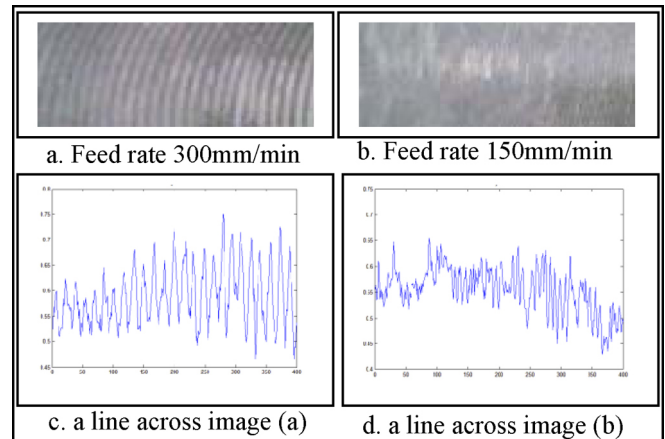


Figure 7. Examples of machined surface images and resulting intensities

V. EXPERIMENTAL SETUP

An experimental rig is developed for verifying the proposed methodology, where an Intelitek – Super pro-light 1000 CNC milling machine is used. Two 5MP cameras type Logitech C910 are used in the developed rig where they attached on both sides of the machine spindle, Fig. 4. The images are acquired at 2592×1944. Both cameras are connected to the desktop PC for processing and controlling the acquired vision data. Ambient light is used to minimize light reflection from the metal work-piece. To facilitate the air blast control, a 12V normally closed solenoid valve is used to control the on/off action of the air blast system.

VI. RESULTS AND DISCUSSION

Validation of the developed system has been carried out experimentally. System programs are developed using MATLAB. Machining tests are carried on square area (100×100) mm of aluminum work-pieces. □8mm HSS end-mill cutter is used in the conducted machining experiments. Source G-code programs SGPs are prepared to include all possible linear and circular tool path combinations. Follow is a representative example of conducted experiments.

Fig. 8 presents an example of a developed SPG which includes 21 tool path movement blocks. Both linear interpolation (G01) and circular interpolation (G02/G03) are used in this SPG. Path simulation is also provided in Fig. 8 for completeness.

The SPG is fed to the (Super pro-light 1000) machine controller. The machine controller is equipped with CNCBase software (version 4.3.0.6). This version of machine software does not allow G-code subprogram call from outside its programming and editing environment, hence, chain to program method (M20 block and followed by files' path and name) is used to call subsequent G-code programs of the NGGP.

The developed segmentation module opens and loads the SPG using a line by line sequence. If a machining block (G01, G02, and G03) is detected, the values of X, Y and Z coordinates of each tool path entity are extracted and the entity machining length is calculated and segmented into a

predefined segments length. Segment length of 10mm is selected in the conducted experiments to suit both surface roughness evaluation requirement and employed cameras resolution. Proper machining blocks of the tool path segments are generated and recorded in a set of G-code chained programs (M20) within the output NGGP. Control blocks of the air blast system are also added in each chained G-code programs of NGGP files, where (M25 Hxx) block is used to switch on the air blast solenoid and (M26 Hxx) block is used to turn the solenoid to off status. Waiting block (G04 Fxx) is also added between M25 and M26 codes to set the time required for air blast on.

The programming algorithm for the camera selection module is also successfully tested and verified. The processing methodology used in this module is based on extracting the tool path direction from the most recent executed G-code program of the NGGP. The extracted machining movement is then used to decide which camera to be activated and used to acquire vision data.

The adopted methodology used for signals synchronization sent and received by both host computer and CNC machine controller is also verified experimentally. Pins (7) and (8) of the host computer RS232 serial port are used for sending and receiving of signals. These signal channels are monitored and controlled by a developed procedure running under MATLAB. Whereas the input/output channels provided by the CNC machine interface panel are used to facilitate the interfacing of the machine with the host computer.

Fig. 9 presents a sample of the NGGP chained G-codes. The value of feed rate in each G-code file is automatically adjusted to enhance surface roughness. A new feed rate value is determined using results obtained from extracted image information. This adjustment of feed rate values is performed in real time just before the CNC controller loads relative G-code program. To control timing and program overlap resulting if CNC machine loads a G-code program that is currently used to adjust its feed rate value, timing and synchronization is achieved by the implied communication and control which proved to provide successful implementation of the developed system.

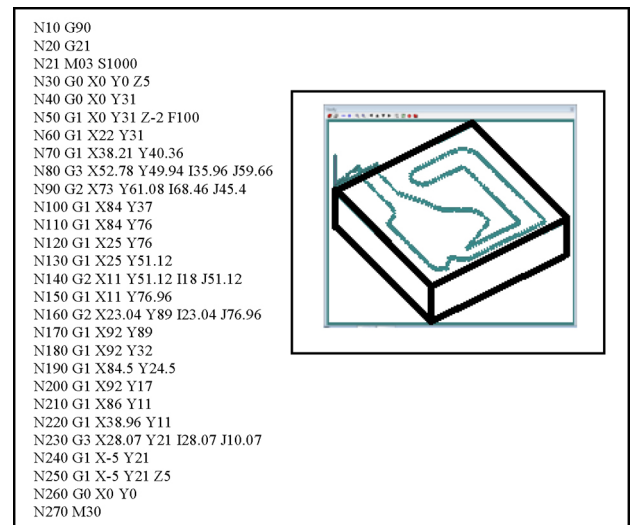


Figure 8. Example of a developed SGP and its path simulation.

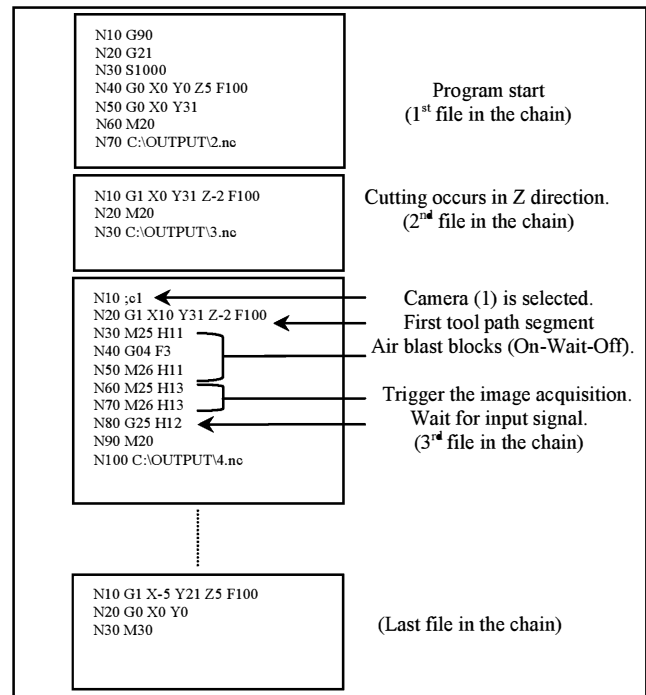


Figure 9. Resulting NGGP of the Fig. 8 SGP.

VII. CONCLUSIONS

An experimental rig is developed successfully and used to assess the proposed methodology. The automatic segmentation approach of source G-code programs showed to be a valid technique that enables the vision systems evaluate the most recent machining of tool path segment. Hence adjustment of machining parameters for the next tool path segment can take place prior to its actual machining. The proposed air blast technique has also proved its validity to clear out the cameras field of view from cut-chips. The developed algorithm to select and activate relative camera

has demonstrated its effectiveness in providing proper image data of the most recent machining action. Synchronization of programmed tasks and signal communication between the hardware modules of the system is implemented successfully using the developed approach. Results of the conducted experiments assure the validity of the proposed system and encourage further development towards its full scale industrial implementation. Nevertheless, further investigation to improve surface roughness measurement using vision data is needed to provide higher robustness of the system.

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