

Optimization of CNC Machine Control for Mapping the Shape from the Image

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Abstract— The article presents research on the development of a system based on a PLC controller used to perform a shape mapping from a photo. The first part of the article shows the system scheme and the operating principle of the developed system. In the second part of the article, the author describes his own research on the comparison of the quality of mapping and drawing time. The author has developed a dedicated algorithm that allows for mapping quality improvement while maintaining a similar drawing time. The article concludes with presentation of the results of practical measurements.

Index Terms—CNC machine, PLC controller, image analysis, optimization

I. INTRODUCTION

THE globalization of the global market economy has led practically all production spheres to achieve more perfect products in a shorter time. With regard to the construction of machines and devices, the need to modify the existing process chains results from the striving to obtain more favourable technical and economic results in competitive production conditions.

In order to increase machining efficiency while meeting the requirements regarding dimension and shape accuracy (narrow tolerances) and surface quality (low surface roughness), the development of machine tools in terms of construction is essential, as well as the development of control systems.

The first machine tools enabling automation of production were hard-wired, which means that they could only perform a fixed, predetermined sequence of movements, without the possibility of reprogramming. The beginning of numerically controlled (NC) machines are the years after the Second World War. The authors of NC machines were the US Air Force and John Parsons collaborating with the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts, USA. After the Second World War the US Air Force gave Parsons's Corporation several contracts to continue the development of innovations in the field of numerically controlled machining. Interested in experiments being conducted at the MIT Servomechanisms Laboratory, Parsons proposed in 1949 MIT to become a project subcontractor to provide expertise on automatic control. Over the next 10 years MIT gained control over the entire project because the Servomechanisms Laboratory's vision of "three-axis continuous path control" replaced Parsons's original concept of "depth cutting positioning" [<http://museum.mit.edu/150/86>].

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The sequence of control information in the form of letters and numbers is called the NC program. In the 1970's, thanks to the rapid development of microcomputers based on NC control systems, Computer Numerical Control (CNC) systems were created.

NC technology has caused an amazing revolution in the manufacturing industry. Almost every company in the industry is equipped with machine tools or numerically controlled machining centres.

Due to the development of electronics and computer science technology and the fact that microelectronic equipment has become cheaper and more available, almost everyone can do their own simple CNC machine. For this purpose the programmable logic controllers (PLCs), servomechanisms and servo motion controllers can be used.

The purpose of this article is to show how to optimize the speed of mapping of shape from an image by a simple CNC machine built from the before mentioned components.

The fact of using the existing elements (such as microprocessor devices, PLC controllers and additional modules for these devices) to build a CNC machine has some drawbacks. Such components do not always have all the necessary functionality for the user. However, they have an undeniable advantage – low price.

CNC machine manufacturers often offer customization of the machine. Thanks to this one can receive a product that perfectly fits the expectations. On the other hand, such devices are much more expensive.

The aim of the work described in this article was the implementation of a simple 2D plotter that allows to draw the shape shown on a piece of paper.

The system assumption was to use a smartphone (for quick image capture) and PLC (with additional modules for servo control) as a 2D plotter. To perform this task, an Android phone and the PLC (with additional modules) from General Electric were used.

II. PLC MOTION CONTROLLER

Each of the leading PLCs manufacturers offers modules for controlling servo drives. This chapter will present the possibilities of such modules on the example of the PACMotion Multi-Axis Motion Controller (IC695PMM335) manufactured by GE [1].

This module can control up to four servo axes and supports discrete and synchronous motion control.

Table I presents the types of movements that can be carried out using this motion controller.

TABLE I.
DESCRIPTION OF POSSIBLE MOVEMENTS

Type	Name and description
Discrete motion	Home – execute a Find Home sequence to establish a valid actual position
	MoveAbsolute – move to a specified absolute position
	MoveAdditive – move a specified distance in addition to the prior commanded distance.
	MoveRelative – move a specified distance relative to the actual position at the time of the execution
	MoveSuperimposed – move a specified relative distance in addition to an existing motion
Continuous motion	JogAxis – jog axis forward or backward
	MoveVelocity – move axis at a specified velocity
	MoveAdditive – move a specified distance in addition to the actual position at the time of the execution
Cam programming	CamIn – performe curvilinear motion defined by means of CAM profiles

All types of motion listed in the table (except for the cam programming type) are by default straight movements. However, it is possible to implement a curvilinear movement. For this purpose, the following parameters (each type of movement is described by a number of parameters) must be properly configured: speed, acceleration, jerk [1].

Drawing the specific shape (using discrete and continuous motion) is not a trivial issue. At the beginning, the motion equation should be precisely defined. Then, for the given equation, the previously mentioned motion parameters should be calculated. This is a time-consuming issue and is not always possible to provide the expected results.

In order to implement a nonlinear motion, the manufacturer prepared the possibility to design the shape that the servos should perform.

The user can prepare his own cam profile with the help of the PACMotion programming tool (editor). Cam profile design is carried out by marking nodes on the axes. In the editor, it is possible to interpolate the movement between the entered nodes using the polynomial of a selectable degree (1, 2, 3, 5). The cam profile, prepared in this way, can be load into the PLC and followed by the servo motion controller.

It should be noted that cam profiles do not allow all shapes to be drawn. Complicated shapes (that are not functions in the mathematical sense) can be implemented by many short discrete movements (e.g. MoveRelative). These are default straight line movements. However, with a properly small step,

the curvilinear motion can be also performed using that type of movement. The disadvantage of this solution is the fact that the drawing process is very time-consuming. For this reason, the author decided to develop an algorithm for optimizing this type of motion. The optimization algorithm is presented in section 4.

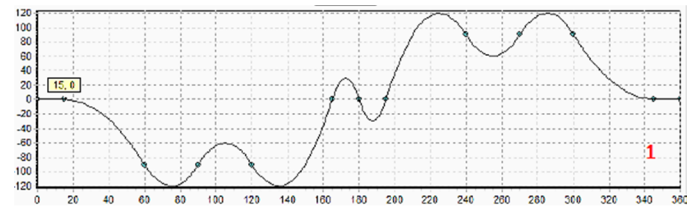


Fig. 1. CAM profile editor

III. THE PROCEDURE FOR DRAWING A SHAPE FROM AN IMAGE

The system operation procedure is shown in Fig. 2.



Fig. 2. System operation procedure

The first step is to run a mobile application. Then the user has to start the camera. All subsequent points of this algorithm are performed automatically. When scanning the image, the algorithm (corner detection) searches for an A4 sheet. If a sheet is detected, a photo is automatically taken. Then, the saved image is converted to a greyscale. After this, the prepared photo is binarized. In the next step, black pixels searching method is executed. Then the black pixels coordinates are sent to the PLC. In the last step of the algorithm, the PLC draws the given shape[2][3][4][5].

The corners detection function is based on Harris Corner Detection function [6][7]. Its general operating principle is as follows:

1. Calculating the quality of the corner for each pixel of the image,
2. Searching for maximum values of corners,
3. Inclusion of the *qualityLevel* parameter (a parameter determining the minimum quality of the corners) and rejection of pixels that do not meet this requirement,
4. Sorting the quality of the corners in descending order,
5. Returning the position of pixels meeting the above conditions; the number of pixels returned depends on the *maxCorners* parameter.

IV. METHODOLOGY OF THE MAPPING SPEED OPTIMIZATION

The speed of the CNC machine is a very important element. However, it should be emphasized that maintaining high accuracy of mapping is also very important. During the tests, it was observed that sending all pixels to the PLC is time consuming. It does not bring significant improvement in the quality of mapping, only causes a notable increase in the time needed to draw the shape. For this reason, it was experimentally noted that the best results (taking into account the speed of operation and the quality of the mapping) were obtained for the situation in which the CNC machine takes into account every second pixel. When more pixels were omitted, the quality of the mapping decreased significantly. Due to the fact that the servo controller moves between pixels on straight lines, it was decided to develop an algorithm that would allow some pixels to be omitted if they are on one straight line.

The algorithm workflow is as follows:

1. The coordinates of the previously selected black pixels are saved to two *pixelX* and *pixelY* arrays.
2. The distances between the first pair of pixels and the next pair are calculated. Distances are calculated using the Pythagorean formula:

$$a^2 + b^2 = c^2$$

3. The absolute value is calculated from the difference of these distances.

$$distance = \sqrt{x^2 + y^2}$$

4. If this absolute value is smaller than the 0.41 coefficient (experimentally determined for the tested shapes), intermediate pixels of these distances are omitted.

V. TEST STAND

A simple CNC machine was built from General Electric components. It is based on PLC with additional modules:

- Basic cassette – IC695CGS012
- Power supply – IC695PSD040
- Central Unit – IC695CPE305
- Ethernet communication module – IC695ETM001
- Servo control module (multi-axis motion controller) – IC695PMM335

- Input module – IC694MDL660
- Output module – IC693MDL940
- Servo amplifier – FANUC A06B-6130-H002



Fig. 3. Test stand – PLC with additional modules

The purpose of the described CNC machine is to receive data (pictures) from the mobile phone and realize the shape found in this image.

The block diagram of the control system is shown in Fig. 4.

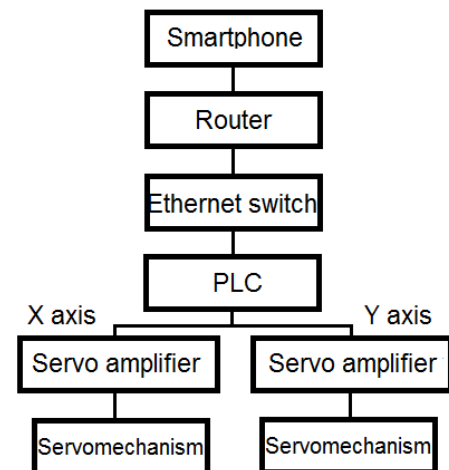


Fig. 4. System block diagram

The main control tool is a mobile device. It is responsible for an user's interaction with the system. The duty of this block is to process signals from the user and forward them to further actuators.

Intermediary blocks that ensure communication between the mobile device and the industrial controller are the wireless router and Ethernet switch. The router makes it possible to connect both wireless and wired devices to one network. The mobile device connects to the Wi-Fi network created by the router wirelessly, while the industrial controller is connected with an Ethernet cable. The block connecting the segments of the router network and the communication module of the industrial controller is the Ethernet switch.

The main element responsible for processing received signals from the mobile device through the application is the industrial controller (PLC). This element together with the appropriate modules is responsible for forcing the movement of the X axis and the Y axis of the plotter. Axis motion control is carried out from the level of the industrial controller program.



Fig. 5. 2D plotter controlled by PLC with motion controller

To make the axis movement possible, it is necessary to use a matched amplifier. Communication between the industrial controller (motion controller) is performed via a fiber optic link. The executive element of the plotter control system are two servo drives which are responsible for the movement of the X axis and the Y axis.

VI. RESULTS

This section shows the plotter mappings for different values of the mapping accuracy. Three shapes with different waveforms were presented to verify the plotter behaviour in different situations. For each shape, a table with mapping data and a series of comparisons drawn by the plotter with the original drawing is presented.

For the plotter to accurately reproduce the shape from an image, it is not necessary to send each pixel. This method would significantly slow the operation of actuators. For this reason a variable “pixel_selection” was created. It determines how many pixels will be sent to the controller:

- 1 - every fourth pixel is sent
- 2 - every third pixel
- 3 - every second pixel
- 4 - pixels specified by the line detection algorithm are sent

In order to compare the operation of the optimization algorithm, it was decided to compare the quality of the mapping. The quality is specified in percent and it defines how the line drawn by the device coincides with the original line.

TABLE II.
DRAWING TIMES FOR SHAPE NR 1

pixel_selection variable	Drawing time [s]	Number of pixels
1	14:55	71
2	17:93	94
3	24:38	142
4	17:55	87

TABLE III.
DRAWING TIMES FOR SHAPE NR 2

pixel_selection variable	Drawing time [s]	Number of pixels
1	15:45	74
2	19:91	98
3	24:73	148
4	19:95	99

TABLE IV.
DRAWING TIMES FOR SHAPE NR 3

pixel_selection variable	Drawing time [s]	Number of pixels
1	16:98	75
2	20:71	105
3	26:44	150
4	14:77	63

It was decided to select two cases for comparison. These two cases were chosen due to the similar drawing time. In this way, one can compare the results of two algorithms implemented at a similar time. The figures show the comparison of system operation based on the “pixel_selection” variable.

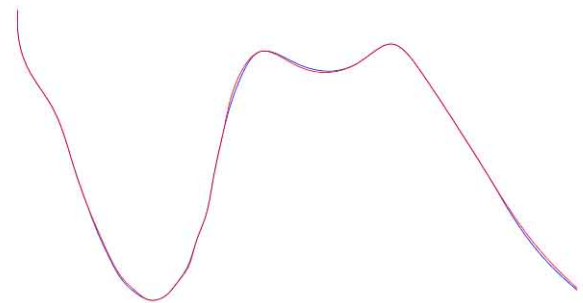


Fig. 6. The mapping of a shape nr 1 (pixel_selection equals to 2)

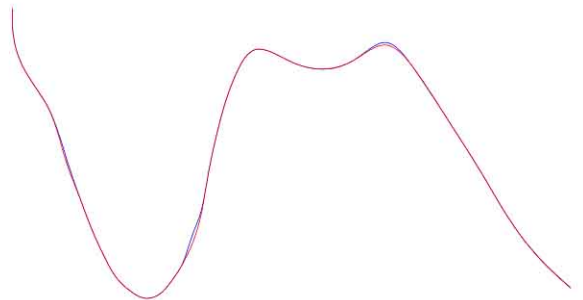


Fig. 7. The mapping of a shape nr 1 (pixel_selection equals to 4)

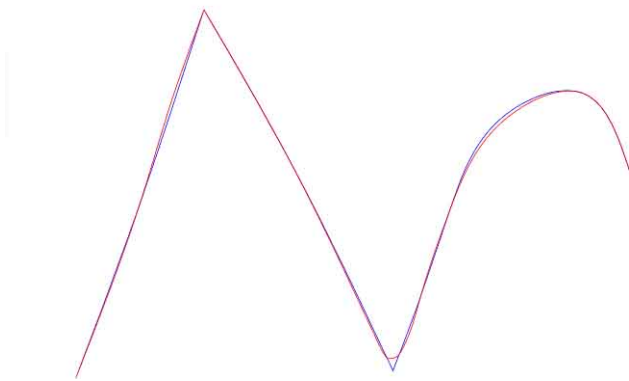


Fig. 8. The mapping of a shape nr 2 (pixel_selection equals to 2)

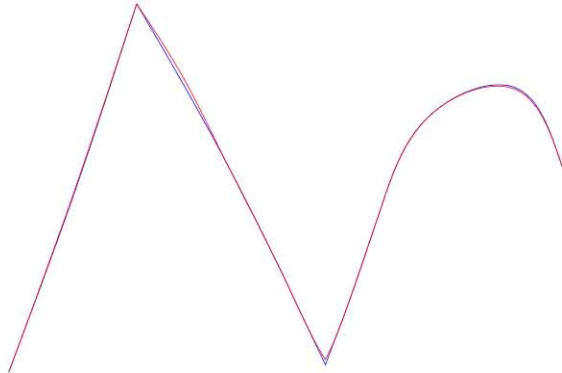


Fig. 9. The mapping of a shape nr 2 (pixel_selection equals to 4)

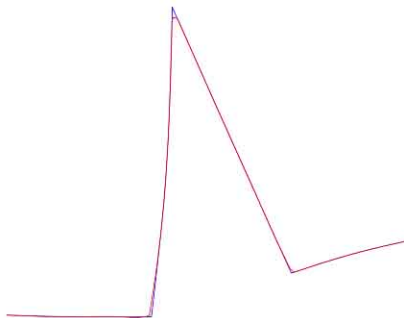


Fig. 10. The mapping of a shape nr 3 (pixel_selection equals to 1)

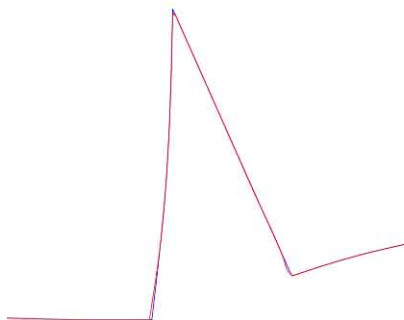


Fig. 11. The mapping of a shape nr 3 (pixel_selection equals to 4)

Table IV shows the results of the comparison of the mapping accuracy for the selected two cases. As it has been shown for similar drawing times, the accuracy of the mapping is greater for a case using a line detection algorithm. Precision mapping shows the percentage of coverage of two trajectories. A value of 77% means that 77% of the plotter's mapping coincides with the original trajectory.

TABLE V.
COMPARISON OF THE MAPPING ACCURACY

Drawing shape	pixel_selection variable	Drawing time [s]	Mapping accuracy [%]
1	2	17:93	77
1	4	17:55	89
2	2	19:91	80
2	4	19:95	86
3	1	16:98	95
3	4	14:77	96

VII. CONCLUSIONS

The studies presented in the article focused on two issues. On the one hand, they concerned the development of procedure for drawing (with the use of an industrial controller equipped with servos) a shape from a photo. On the other hand, a comparison of four drawing methods has been made. The methods differ from each other in the way of selecting drawing points of a given shape. For the three ways, points were chosen arbitrarily. The fourth way is based on a developed algorithm that allows an user to optimize the mapping in terms of time and quality. The results comparing the drawing time are shown in the tables. In addition, for the two selected cases (similar times of drawing) a comparison of mapping quality is presented.

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