Machine Vision for Selective Polymer Curing Devices: Challenges and Solutions

Maxim Ya. Afanasev, Yuri V. Fedosov, Anastasiya A. Krylova, Sergey A. Shorokhov
School of Computer Technologies and Control
ITMO University
St. Petersburg, Russia
amax@niuitmo.ru, yf01@yandex.ru, {ananasn94, stratumxspb}@gmail.com

***Abstract*—Designing a device for printed circuit boards (PCB) job production is a challenge requiring a reasonable compromise between the cost of manufacture, accuracy and quality and the compatibility of the equipment with existing production control systems. The use of computer vision technology plays an important role in the automation of the production process and delegating routine operations like recognition of the work piece and calibrating the machine to the computing equipment. This paper describes design problems, execution and implementation of the technical pattern recognition module as a part of a selective polymer curing devices' control system. It also examines challenges to the application of image processing methods, methods of marker search navigation, as well as options for using the system in the production process.**

I. Introduction

Machine vision formed as a separate area in the early 70's. Currently, it is widely used due to affordable prices of hardware components including cameras and powerful computing resources. As a consequence of The Fourth Industrial Revolution, it started being actively applied in cyber physical production systems (CPPS) [1]. CPPS allows us to interact with the "physical" world through its components that observe and record "physical" world parameters and events. Obviously, machine vision can be one of the ways to link the real world and its virtual twin. Foremost, machine vision's main tasks are identification (e. g., barcode or QR-code scanning), transitional and final control, and work piece (product) or instrument positioning. Behind each task stands various image processing algorithms. However, a detailed list of tasks depends on specific production.

Currently, no electronic device operates without printed circuit boards (PCB) in it. PCB differ in configuration (one-sided, two-sided and multilayered boards), geometry, accuracy, etc., that impacts a manufacturing technology choice altogether. The number of units to produce is important as well. A production type (job, batch, or mass) determines a manufacturing technology according to money and time costs for the production process and preliminary preparations. So, for example, in mass production, photomasks are usually used, which is not profitable in job production due to high manufacturing costs.

Often PCBs are required at the product development stage where the prototype is created. After creating the prototype on the breadboard it becomes necessary to produce a prototype closer to the final product. In this case, PCM replaces the breadboard.

The manufacturing of PCBs (especially multilayer) is a very complex process. Simplified, it can be divided into the following main stages:

- Drilling holes in the work piece and metallization
- Coating of the work piece with a photosensitive polymer (photoresist)
- Photoresist exposure through the template (UV curing)
- Development and removal of photoresist
- Coating of the solder mask and screen printing (UV curable photopolymer is also used)

Despite the fact that there are numerous automated devices specified for operations on each step, all of them are pretty expensive and therefore not suitable for the production of prototypes. Consequently, PCB production of prototypes is usually done manually, which undoubtedly negatively impacts their quality.

Designing a selective polymer-curing device for small batch and job production is challenging as it requires a combination of a reasonable price, acceptable accuracy, and a noticeable quality improvement in contrast to manual production. Moreover, due to the fact that the modern industry is constantly undergoing changes it is important to make the device flexible and interoperable. Interoperability is one of the most significant properties of CPPS that allows various software and hardware from different producers to exchange information and make use of it.

Interoperability is an important characteristic of a distributed system due to the necessity to interconnect various devices from different producers. It is a comprehensive concept and usually represents as seven layers—technical, syntactic, semantic, pragmatic, dynamic, conceptual and organisational. The first one deals with a communication protocol and hardware interfaces. Syntactic and semantic support data format and ontologies respectively.

Pragmatic layer often describes functionality discover methods and dynamic layer deals with monitoring process. Conceptual and organisational layer are the heights levels provided knowledge about the goals of business models. To obtain

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a distributed CNC system for modular equipment first five layers—technical, syntactic, semantic, pragmatic and dynamic ? are necessary. Flexibility is an ability of the system that allows it to adapt depending on production conditions such as production capacity and product nomenclature. The usage of the machine tools possessing these properties can be really profitable for job productions and small fabrication experimental laboratories. Therefore, it was decided to implement a selective polymer curing device based on reconfigurable machine tool (RMT).

Generally, RMT consists of replaceable hardware and software modules. However, it can have a permanent base element such as a coordinate table and its control system. External modules such as milling head, drilling head or extruder for 3D printing are substitutable. For example, the external smart laser head (SLH) block has to be mounted for selective polymer curing. Given the above, machine vision can be considered both an external and a permanent block. As an external block, it has to contain knowledge about the application domain. For instance, to use it in PCB diagnostics, special algorithms for defects recognition has to be provided. As a permanent block, it can carry out basic positioning tasks by the list of standard markers with reference points or just perform simple monitoring functions.

In summary, there are three main machine vision challenges in PCB production using the selective polymer curing method:

1) Search of reference points
2) Real-time and post production defects recognition
3) Real-time monitoring function

The rest of the paper is structured as follows. The related work was carried out on PCB production is addressed in Section 2 as well as machine vision application. Section 3 defines main challenges of machine vision in PCB production. Also, the compression between Roberts, Sober and Canny filter is provided. Figures with results of the compression are shown in the same section. In Section 4, implemented machine vision system is described including marker recognizing algorithm and the camera hardware characteristics.In Section 5, some limitations of the developed system are discussed as well as future plans such as work with curvilinear surfaces. Section 6 contains a conclusion and future plans concerning system development and improvement.

II. Related work

Since the late 90's a lot of work has been carried out dedicated to RMT most notably by Koren et. al. [2], [3]. They were one of the founders of the reconfigurable production systems (RMS) paradigm and made the first RMT and defined the main concepts of RMS and RMT. The scientists worked around the RMT software side as well as mechanics. Their RMT control system has open architecture due to the necessity of changing the software dynamically keeping the control system robustness. Moreover, to handle the challenge they implemented configuration and simulation tools. Additionally, a great deal of attention was paid to the cost-effectiveness of RMT compared to other conventional approaches such as dedicated machine tools and general-purpose CNC machine tools.

However, the market is changing and it is important to consider the RMT cost-effectiveness. Therefore, academics from Italy recently provided a detailed economic framework and a justification of RMT benefits. Furthermore, they transformed the paradigm of RMT into a "Lego-like" reconfigurable machines paradigm and examine its productivity and cost-efficiency under conditions of modern industry. Despite the benefits, they did note some challenging management problems attending "Lego-like" reconfigurable machines usage [4].

There is a multitude of academic work around the application of machine vision in PCB production. For example, Huang et. al. are working on machine vision application in the electronic industry for a micro-drill process. It allows them to determine grinding parameters automatically for the correction of defective holes [5], [6]. Wei-Chien Wang developed a similar system for measuring drilling quality of PCB differs in the ability to determine multiple defects such as missing holes, incorrectly located holes, and excessive holes [7].

A significant number of studies are devoted to the use of machine vision for the inspection of PCB [8–10]. Academics from National Tsing Hua University proposed the elimination-subtraction method for PCB defects recognition [11]. J.Gómez used for these purposes both machine vision and traditional methods [12]. Moreover, machine vision is used with a neural network to detect and report IC lead defects online [13]. For PCB inspection in job production, scientists from Bandung Institute of Technology created an inexpensive machine-vision system for PCB automatic optical inspection [14].

In addition to traditional PCB production methods, 3D-MID technology is gradually spreading. The main idea of this technology is to place electric schemes on the complex shaped three-dimensional surfaces from plastic. Obviously, it is a new challenge for machine vision in the electronic industry due to inevitable complexity of algorithms and an increase in the performance of computing resources. There are different producing methods according to 3D-MID technology, but the most common is laser direct structuring (LDS) that actually occupies more than 90 % of market share. This method belongs to the LPKF Laser & Electronics company that develops and produces various machine tools implementing 3D-MID technology. Some of their machine tools are equipped with a sophisticated machine vision system that is used for the detection of fiducial marks, part contours and significantly simplifies structuring in different positions [15].

III. Design and implementation

A considerable number of methods of processing images exist and are divided by the type of task performed, complexity, and accuracy of the results. Of course, we cannot say that there is a kind of universal solution in the field of recognition algorithms; therefore, in the implementation of a technical problem, research on the subject domain is required. This includes the analysis of the operating conditions of the equipment, the type and quality of the input data, the characteristics of the technical means, as well as the tasks performed by the machine vision system.

A. Operating conditions analysis

When dealing with industrial equipment, even if it is very small, it is important to understand that the environment in which the processing takes place is not ideal. First of all, affects include the surrounding space, such as dust, vibration, illumination and other factors. The stepper motors of the photopolymer curing machine will not work smoothly enough to exclude the vibrations transmitted by them to the carriage.

B. Input data information

The main algorithm input data are the reference markers on the workpiece, which help to determine the zero point. The reference markers combine two contrasting colours and they are usually applied to the surface of the work piece with the help of a printer at the stage of blanking operations, so the position accuracy and the labelling quality are important for processing. With the same orientation of the blanks on the desktop, you can get by with just one marker, from which the surface will be processed according to the G-code. However, for greater universality there must be at least three of them in the three different corners of the work piece, excluding the right bottom corner.

The reference markers can also be subdivided in size and shape (Fig. 1). The size should be determined by the camera resolution, that is, so that when processing the frame, the marker could be determined accurately, but not too large to not take up a large amount of space on the work piece's surface.

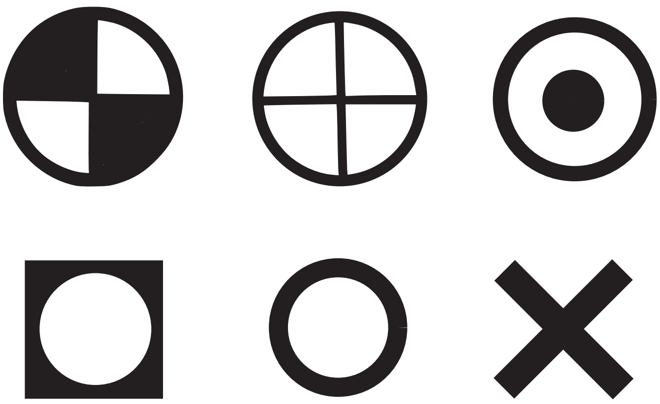

Fig. 1. Examples of reference markers

C. Software

According to the description of the technical component of the platform, cited in previous work [16], the module of machine vision is equipped with an Odroid-C2, single-board microcomputer based on the quad-core Amlogic ARM Cortex-A53 processor with a clock speed of $1.5\,\mathrm{GHz}$ and $2048\,\mathrm{MiB}$ RAM. Also it has a set of interfaces and supports UNIX-type operating systems like Ubuntu, Android etc. From this it follows that in implementation it is necessary to adhere to productive and undemanding methods of processing input frames in order to provide the necessary processing time, sufficient to provide "real-time" work.

D. Tasks performed with the module

The theme of the tasks assigned to the component was already touched upon. These include the search for markers, tracking the shape of the laser spot, transferring video to the user application and monitoring the processing. The video-stream transmission often takes a long time to work the module and can affect the performance of other functions, so it is advisable to separate it from the common system with its own camera and its own data transmission channel.

TABLE I. COMPARISON OF FILTERS

Comparison option	Roberts filter	Sober filter	Canny edge detection
Size of mask	2×2, 3×3	3×3	5×5
Number of stages	2	2	4
Gradient detections	2	2	4
Input image	greyscale	greyscale	any
Noise suppression	no	no	yes
Detect edges share	$65\,\%$	$80\,\%$	$90\,\%$

E. Processing algorithm

From the description of the input markers, it was discovered that the grey scale images, represented as two-dimensional arrays of numbers in the range [0–255], are enough as input frames. The conversion of the image into a halftone must occur when the input frame is processed first by the eq. (1):

$$\mathcal{G}_s = \frac{\mathcal{R} + \mathcal{G} + \mathcal{B}}{3}\,, \tag{1}$$

where $\mathcal{G}_s$ is the brightness value of the pixel in the grey scale image, and $\mathcal{R}$, $\mathcal{G}$ and $\mathcal{B}$ are respectively the brightness values of the red, the green and the blue components of the pixel of the original input image [17].

Most of the task is performed by the gradient analysis of the image, at which changes in the brightness of pixels on the borders are highlighted; it allows for the determination of the presence of a mark on the indicator of the highest contrast in this region. Later, when threshold binarization is carried out, the extra boundaries are removed and only those belonging to the label remain. There are a number of methods for performing gradient analysis and comparing their characteristics to determine the most suitable choice.

As shown in Table I, the most accurate result is provided by the Canny filter, but it is also the most resource intensive of all those presented because it calculates a gradient in 4 directions and has a number of refinement calculations. It is established that the application of the Canny method does not allow real-time processing of the frames on the equipment used and the process time can reach $100\,\mathrm{ms}$ [18]. Since the processing time depends on the image size, it can be increased by decreasing the resolution of the camera, but the accuracy of the detection will suffer and the label may be too small on the frame.

Proceeding from this, the Sobel filter was selected, which provides acceptable accuracy with a small number of computations. The Sobel filter uses gradient analysis in two directions of the image, that is, multiplies each of the image pixels by the 3×3 element mask (Fig. 2).

-1	0	+1
-2	0	+2
-1	0	+1

Gx

+1	+2	+1
0	0	0
-1	-2	-1

Gy

Fig. 2. Sober mask

F. Moving problem

However, processing is only half of the work of the machine vision component. A significant influence on the result and speed of work is the movement of the camera when searching for markers. Obviously, the easiest way is to move the camera around the field line by line, covering in one pass some part of the working area. The size of this area S depends on the field of view (FOV) area covered by the camera in one frame and it can be calculated by the eq. (2):

$$S = 4h^2 \cot\frac{\alpha}{2} \cot\frac{\beta}{2}, \tag{2}$$

where h is the height from the camera lens to the surface of the work piece, and α and β are the angles of the FOV in the vertical and horizontal dimensions of the camera. With knowledge of these values, one can roughly specify the coordinates of the movements during the search, but there are difficulties in determining the labels.

Therefore, when finding one random marker, it can not be said exactly where it is on the work piece. Two ways out of this situation can be assumed:

1) Direct run through all the "rows" of the working field with the record of the coordinates of the marks found. It can work if there are more than three markers (for example, on non-rectangular shaped blanks) and does not require great accuracy in their determination since vibrations of the movable carriage of the machine, on which the camera is fixed, can introduce errors into coordinate values. With this method, the whole working field is examined without fail.
2) By changing the shape of the main marker relative to the other two, a straight run is performed until it is found. Furthermore, the camera centres on it and, knowing where the remaining two markers are located, moves to their side before centring on them with a further return to the main one. The recording of the coordinates of additional markers can be calculated based on the dimensions of the field of view of the camera or on the time of carriage movement with a certain speed. In this way, you can determine the dimensions of the work piece without examining the entire working field, and additionally, the work piece position control is monitored to avoid distortions.

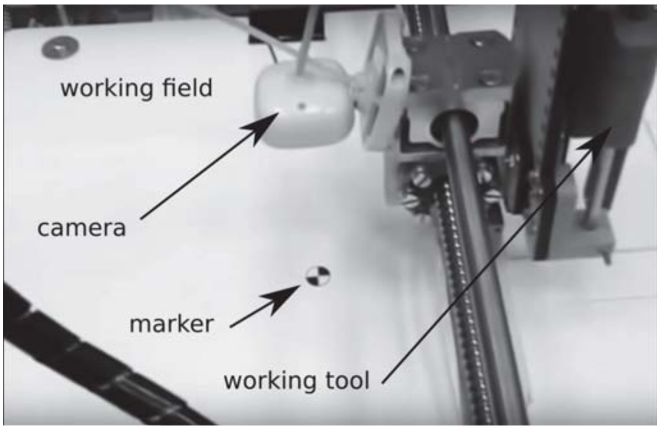

Fig. 3. The testbed

The instructions for moving the carriage transmitted by the machine vision module to the CNC component are determined based on the resulting image. In other words, by defining the marker on several frames in a row, you can begin to centre the frame on it. Knowing the field of view of the camera, it is easy to calculate the distance to which the carriage needs to be moved; otherwise the approximation will be performed discretely, with a certain step size, each time analysing the input image. When the centre point of the frame is overrun, the step can be successively reduced, for example, by dividing it by two, but in this case the centring can take a long time, depending on the resolution of the camera.

IV. Results

The described device for selective laser curing acts as a test bench for the implementation and testing of the algorithm as a component of machine vision and for the entire control system as a whole (Fig. 3). More information about its composition and functionality can be found in the works [19], [20].

First of all, it was decided to implement the functionality on the Python 2.7 platform using the open OpenCV library, which is fairly simple to use and has many implemented functions. During testing, a good processing time was obtained ($30\,\mathrm{ms}$ on average), which can be explained by the low resolution of the camera used (in the early tests a web camera with a resolution of 0.3 megapixel was used), but in combination with a resource-intensive library. After searching for the marker, the program began the process of centring on it, sending control commands directly through the serial port to the control unit of the installation. Movement control in any of the four sides is formed through the command of the beginning of the movement and the command of the end of the movement.

In one simple test, the component had to find a label, combine its centre with the centre of the frame, and then send a signal to the beginning of the execution of the control program. In general, the work of the algorithm for determining and centring can be described in the form of the algorithm 1.

Obviously, this method of control is at least easy to implement, but depends on the frame rate provided by the algorithm. The shift begins when a number of conditions are met, but does not stop until the centres coincide, analysing the

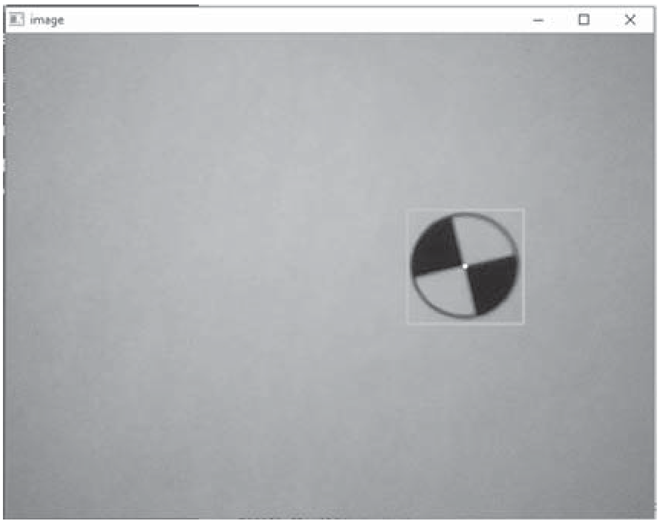

Fig. 4. The camera view

Algorithm 1 The algorithm for determining a marker and centring tool

$frame \leftarrow \langle x, y \rangle$
$markerCenter \leftarrow \langle x_m, y_m \rangle$
$fieldOfView \leftarrow \langle width, heigth \rangle$
$timeOfShift \leftarrow 0$
$fieldOfView \leftarrow angle$
$\mathcal{V} \leftarrow speed$
if $\exists marker$ **then**
    $markerCenter \leftarrow \langle x_1, y_1 \rangle$
    if $markerCenter[0] < frame[0]/2$ **then**
        $timeOfShift \leftarrow fieldOfView * ((frame[0]/2 - markerCenter[0])/frame[0])/v$
        MOVELEFT( )
        DELAY(timeOfShift)
        STOPMOVING( )
    else if $markerCenter[0] > frame[0]/2$ **then**
        $timeOfShift \leftarrow fieldOfView * ((markerCenter[0] - frame[0]/2)/frame[0])/v$
        MOVERIGHT( )
        DELAY(timeOfShift)
        STOPMOVING( )
    else
        CONTINUE( )
    end if
    if $markerCenter[1] < frame[1]/2$ **then**
        ▷ Same for up and down moving.
    end if
    SENDREADYSIGNAL( )
end if

marker's position of the tag frame by frame. In other words, while the centre of the marker does not match, the incoming frame will go through all processing steps to determine the position of the marker, and while the processing is being performed, the movement will be carried out.

In the further work, the component used an IP camera with a Wi-Fi video transmission interface, capturing frames at 1280×920 resolution (see Fig. 5). The camera software provides the H.264 video compression standard with a frame rate of 25–30 frames per second in maximum resolution, and also makes it possible to work with the real-time stream transmission protocol (RTSP) and the file transfer protocol (FTP). When working with it, the FOV parameters are defined as 65 degrees (usually), which makes it possible to determine the covered field with some tolerance and to implement a new shift algorithm without using frame analysis with the carriage movement and with greater accuracy and speed.

Fig. 5. The camera used for experiments

As for the transfer of the video stream to the client application, as noted earlier, such a component function should work in isolation from the main system, so as not to load the processing algorithm. To implement this function, it was decided to allocate a separate camera located near the base and having its own data transfer channel. The video stream is transmitted over the communication channel using the RTSP technology upon receipt of a request from the client's application.

V. DISCUSSION

The main reason for using computer vision systems in industrial equipment is the task of automating routine operations, which reduces the time to create a PCB prototype, but at the same time, it must be flexible enough and universal since it is not highly specialized equipment. The range of possible types of products, in this case, can be very large, which leads to the inevitable complication of software, the increase in requirements for receiving devices and the consideration of a large number of input options and their correct interpretation.

Based on the received results, at the moment it can be said that the recognition system is implemented with the ability to determine one or more markers on flat work pieces and to centre the camera on the selected marker, based on the input image analysis and the camera shift distance calculation. The speed of execution of the algorithm can be considered close to "real time" work.

However, as the main limitation in operation, one can note the non-switchable infrared filter in the camera used. The IR-cutter is necessary in order to limit the part of the light that hit the lens, making the image close to real; however, it reduces the sensitivity of the image perception and requires normal illumination on the desktop. For the recognition system to work, it is more advisable to use a camera with a switchable filter, which can improve the accuracy of identifying the marks on the frame and will allow working in conditions of low illumination.

Another, but not less important task is how to work with curvilinear surfaces. To solve it, the control system needs for a new displacement algorithm due to altitude changes, working with a large number of markers with different angles, and taking into account their size and shape changes. The principle of working with surfaces of arbitrary shape can be compared with the principle of 3D scanner functionality, and accordingly, may require more productive industrial equipment.

VI. Conclusion

In this paper, questions of the use of machine vision in the design of devices for the PCB production were considered. These types of products are characterized by the complexity of manufacturing, which requires high accuracy of positioning and processing, as well as sterility in the processing area, so the reduction of manual labour during operations is necessary for the design of modern high-performance platforms. Based on this, it can be concluded that the introduction of vision systems in the equipment management system increases the level of automation of the production line. This is true not only for highly specialized equipment, but also for small universal devices that produce single and small-batch production.

The machine vision component is presented as a part of the modular control system, which allows designing it separately from the rest of the system, focusing only on the ways of its interaction with the other modules using specialized protocols and communication channels. This approach allows the design of flexible and scalable control systems, oriented to a wide range of machine tools.

Any computer vision system relies on image processing techniques. The main task of the algorithm is to separate the desired object in the frame and compare it to a certain class, which would allow unambiguous interpretation of the object and use this knowledge in the future process. In the role of input objects for the developed system, there are reference markers applied to the work piece by printing or some other method.

In practical work using the capabilities of the OpenCV library, the algorithm for recognizing markers on flat work pieces with the possibility of centring the camera was tested, as well as the transfer of video stream on demand to the client application. Further work is related to improving the performance of the component and expanding its capabilities, aimed at working with different types of surfaces and forms of work pieces.

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