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Development of a novel visual servoing probe test method for fault diagnosis of printed circuit boards

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Abstract: Printed circuit board (PCB) measurement and repair is a challenging task that requires experience and expertise to perform. PCB diagnosis and repair shops employ skilled operators to carry out the corresponding measurement tasks using measuring instruments (e.g., oscilloscopes, multimeters) in order to uncover the condition of a particular product. However, these tasks are often repetitive and meticulous, and additionally, the results need to be collected and carefully documented so that the gathered experience regarding the product can be re-used when the next product of the same type arrives into the shop. Nevertheless, the diagnosis of used PCBs is less researched and current flexible automation possibilities are limited. In this paper, a novel visual servoing probe test method and measurement tool are proposed to provide a flexible solution for PCB diagnosis with a higher level of automation. The aim of the approach is to reduce the burden on the operators by carrying out the repetitive measurement tasks and automatically storing the results while leaving the responsibility of measurement profile setup to the human expert. The proposed visual servo system uses manually teached-in measurement points, where template patterns are recorded using cameras, and it is capable of compensating positioning errors in the range of a couple of millimeters. The proof of concept of the proposed method is presented through motherboard measuring experiments, with a 99.7% success rate.

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Keywords: Flexible and reconfigurable manufacturing systems, Quality assurance and maintenance, Visual servo control, Printed circuit board measurement, Fault diagnosis

1. INTRODUCTION

Automatic measurement and diagnosis of used PCBs (printed circuit boards) is still a challenging task due to the need for precise fixturing of the boards in traditional measuring tools, as well as the PCB schematics (including the geometry) for programming. Hence, repair shops usually employ human operators to find and identify the root cause of the malfunctions of the broken PCBs. In general, these shops face a large variety of products in small batch sizes but with many, frequently recurring product types. Even though measuring operations often contain repetitive steps – seemingly good candidates for automation – automated solutions can not yet provide such flexibility for repair shops to be worth investing into.

The automatic quality assurance and electrical test methods of the PCB boards are well established for manufacturing. These electrical tests ensure that the bare or populated PCBs leaving the factory are tested thoroughly regarding their electrical parameters (voltages, currents, etc.). There are two main testing approaches: i.) the in-circuit tester system with bed-of-nails fixtures (Mysore et al., 2006), and ii.) the flying probe test (Gómez et al., 2007). The bed-of-nails approach is the fastest testing method due to its massive parallelization with the test-pins in the bed connecting simultaneously to the PCB. On the other hand, this method is the least flexible as it requires a pre-manufactured, accurate fixture, which can only be used for one type of PCB. Accordingly, this method in general is only applicable in mass production of PCB boards.

The elimination of PCB-specific fixtures, and correspondingly, the possibility to set up test programs without fixturing raised interest toward the more flexible flying probe testers. With this, the recurring cost of building specific beds-of-nails was saved. Flying probe tests require accurately set up measurement point positions. These tests can be rapidly prepared from a digital geometric representation (such as a CAD – computer-aided design – model), due to the tight manufacturing tolerances of PCBs. Therefore, flying probe tests are typically used for manufactured PCBs and not for repairing assembled PCB products, where geometric information may be missing. Even if the measurement point positions are defined offline (i.e., with coordinates and not through manual teaching), the points might not be accessible from the usual vertical approach direction because of obstacles (cables, heatsinks, etc.) in the assembly.

Consequently, the diagnosis of used PCBs calls for even more flexible measurement methods. Beside managing a large product range, handling the variation between different products of the same type is also challenging. These variations commonly occur when the production is maintained over a

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longer time period, or when there are multiple manufacturers for some PCB components. Although connection point positions seldom change, having varying visual appearance and dimensions in minor features like heatsinks and mounted components is rather typical. An example PCB comparison with deviations is shown in Figure 1. These deviations raise the need for new testing programs due to changes, like the probe needing to be in a different approach orientation when testing a measurement point to avoid collision. Therefore, automated measurement point detection, together with automated program generation or adaptation would be highly beneficial, which calls for a flexible, robotized solution.

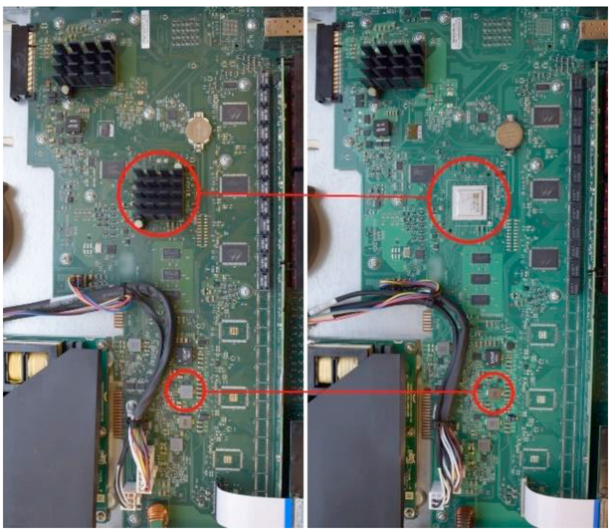

Figure 1. Board color and other deviations between particular workpieces of the same type.

In this paper, a novel, robotic, visual servoing probe test method and corresponding measurement tool is proposed. An experimental PCB measurement cell is developed to automatically measure relevant measurement points of a PCB motherboard without precisely locating the motherboard in the robot workspace. The solution is suitable for repair shops to test PCBs using simple locating pins and basic test specifications, without the need for accurate geometric information about the product.

2. PROBLEM STATEMENT

PCB diagnosis and repair shops are dealing with an immense amount of broken PCB products. They receive hundreds of different PCB types with very small lot sizes where part of the PCB types are consistently recurring. In general, the first step of the repair process is to measure a series of predefined key points on the PCB in question (i.e., to execute a measurement profile) using a multimeter, oscilloscope or other measuring instrument to identify the possible failure cause, or broken electrical component(s). The corresponding – workpiece-specific – measurement points are known to the expert field engineers from the PCB schematic.

The preparation of the measurement is performed by the operator. This includes loading the workpiece into the measuring system, connecting the terminal(s) of the measuring instrument, connecting the communication port to the measuring system, as well as connecting the power cable. This is necessary, as powering on and off, and system booting is almost always required for the diagnosis.

Recurring product types are good candidates for automated, robotic measurement. To reduce the workload on the skilled experts, a robotized measuring process can be developed, allowing these experts to concentrate on creation of measurement profiles, as well as decision making instead of the repetitive, manual work. The automated measurement also enhances the documentation process by automatically collecting and storing data based on the measured PCB and the measurement profile.

More often than not, CAD drawings of PCBs are not available for repair shops, therefore the measurement point positions need to be acquired on-line (i.e., via manual point teaching). A PCB flying probe test can test fine pitch printed circuit boards down to 0.3 mm with a repeatable accuracy of probe placement of 0.05 mm (Russell, 2005). This also defines the tolerance requirement for the automated test cell positioning system. Also, the on-board assembled components such as heatsinks, cables and other obstacles call for the possibility of different measuring orientations (i.e., adjustable probe poses) that need to be defined per workpiece type and per terminal position. These requirements imply the application of a robotized measurement cell, since a 6 degrees of freedom (DoF) robot arm is capable of freely manipulating the measuring pin together with its tool center point (TCP) when mounted on its tool flange.

In classical robotic applications, these problems can be solved using an online teach-in method, where the TCP of the robot pose is set by the operator at the setup phase and the teached-in points are interpolated during the measuring cycle. This method can be performed with the precision determined by the repeatability of the robot, which is usually in the order of 0.1-0.01 mm for industrial robot arms. However, teached-in points can only be used successfully, if the fixturing of the workpieces is precise. Otherwise, the PCB positioning error also needs to be taken into account during the measurement.

This paper proposes a novel visual servoing probe test method, together with a robot-mountable measurement tool, to overcome the challenges of automated PCB measurement in repair shop environments. The method can handle inaccurately located workpieces and move the measurement probe to the measurement point with the required accuracy. The key features of the proposed visual servo probe tests are the following: i.) enhanced flexibility, as no precise geometric representation is necessary for point teaching, only a basic test specification is required; ii.) simple usage, the teaching process only requires pixel point selections on the camera images and an approximate positioning of the robot TCP; iii.) no precise fixturing is required, the visual servo method is capable of compensating a couple of millimeter errors in positioning, and the workspace of the robot arm allows large variation in PCB size; iv.) the technique is robust to deviations in the visual appearance and lighting conditions; and v.) the measurement profile is easy to set up and modify, adding, removing and adjusting measurement points is simple.

3. RELATED WORK

PCB measurement, testing and diagnosis has a broad literature, with the most prominent areas being measurements using bed-of-nails, the flying probe test, and visual inspection of PCBs. However, research typically focuses on the quality assurance of the mass-produced boards, and less attention is given towards the diagnosis of used products.

Research related to bed-of-nails tests mostly focuses on making the testing method more efficient by parallelizing the measurement (Mysore et al., 2006). Although this approach is very advantageous in case of quality assurance of mass produced PCBs, it is inflexible, as for each individual PCB, another fixture and/or bed is necessary. This prevents its application in PCB measurement and repair shops.

Works related to flying probe tests typically aim to extend the existing concept of flying probe tester machines, e.g., with a smart short circuit tester (Kanimozhi and Gopalakrishnan, 2016), or with advanced sequence optimization (Bonaria et al., 2019). Also, Jurj et al., (2020) presented a low cost version in-circuit tester based on the flying prober concept. Compared to the bed-of-nails approach, flying probe tests are slower but more flexible, as a single measurement machine can be programmed for many different PCBs. However, programming generally requires the geometric information of the product in question. Thus, the application is more suitable for mass production, and less applicable in the absence of an accurate digital geometric representation of the PCB.

Image processing-based PCB diagnosis is also well researched. In general, these studies show solutions for identification of visible defects, such as missing, incorrect or incorrectly placed components, poor solder joints or scratches on the surface of PCBs (Adibhatla et al., 2020; Nayak et al., 2017; Teoh et al., 1991). In (Jeon et al., 2022), thermal images are used to detect and classify faulty PCB components, e.g., shorted or opened chips. In the work of Mukhopadhyay et al., (2019), the effect of different PCB shapes and colors, as well as different lighting conditions are analyzed. Electric parameters, on the other hand, are not accounted for, meaning that these methods cannot be used for electric diagnosis by themselves.

On the other hand, vision is also utilized for visual servoing (Chaumette and Hutchinson, 2006) to overcome system uncertainties and improve the overall precision of the system. In case of servoing, the target is set up as the fulfilment of a certain – often precision related – condition. The target pose then can be reached by fulfilling this condition with continuous visual feedback and actuation of the manipulator.

Visual servoing on robot arms is applied in different fields, such as assembly (Chang, 2018), tool changing (Wei et al., 2021), soldering (Shang et al., 2023), or micro-manipulation (Wang et al., 2008). In the work of Banlue et al., (2014), visual servoing is utilized for PCB measurement purposes, for automated fault insertion testing in particular. The task of the servo method is to correctly position the test-pin of the end-effector over a measurement point, which can be either a via hole or a probe site. However, other types of measured features (i.e., non-circular) are not considered.

To the best of the authors' knowledge, there is no such PCB testing solution that is suitable for, or can be effectively applied for robustly checking a variety of features on used PCBs arriving in small batches, especially in case the precise geometry of the product is not available.

4. METHOD

Assuming there are deviations caused by the inaccurate workpiece location, manufacturing and assembly tolerances of the PCB, as well as the robot positioning repeatability, the positioning error can be in the range of a couple of millimeters. To be able to handle the position error of the measured features, a visual servo technique was developed. The idea is to observe the test-pin (connected to one of the terminals of the measuring instrument), and the measured feature simultaneously using a 2D camera. By identifying the axis of the test-pin together with the measured feature, a positioning error can be calculated in the image space, which determines the direction and an estimated magnitude of the required compensation in the physical space. To realize the compensation, motion commands are sent to the robot to reduce the error on the camera images. As planar compensation is required (in a plane parallel to the top plane of the PCB), bi-directional observation is necessary. Therefore, a second camera is introduced, which detects the position error perpendicular to the first one. A corresponding sample image pair is shown in Figure 2.

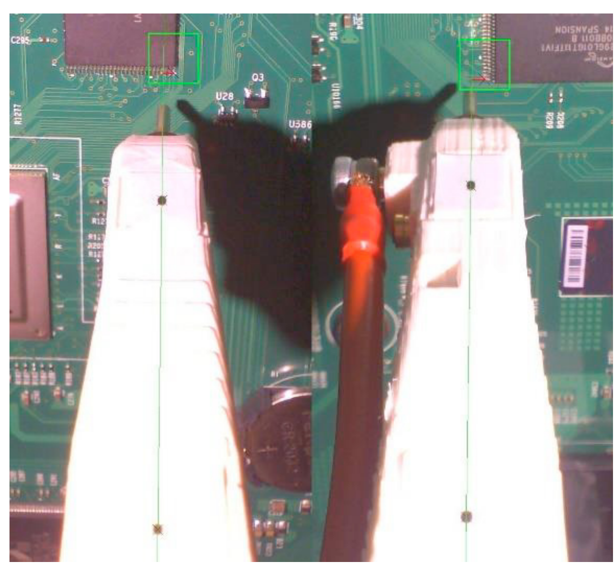

Figure 2. Processed camera images corresponding to the measurement point U82 (both viewpoints) during the execution of the visual servo technique. The found probe axis is shown in green, the found template is highlighted with a green rectangle, and the error is shown with red vector perpendicular to the axis.

When set up properly, the test-pin mounted on the robot converges to the measured feature through the servoing robot motion (the planar motion is performed on a plane above the PCB using a board-specific safety distance to avoid collision with any mounted components). After the error is reduced below a predefined threshold in both directions, the test-pin's axis becomes aligned with the measurement point and using a downward feeding motion along this axis, the electric measurement can be carried out by pushing the test-pin against the measured feature, which establishes the galvanic contact.

4.1 Measurement tool

A low-cost, compact, robot-mountable measurement tool was designed for the realization of the flexible PCB measurement and visual servo function. The main role of the measurement tool is to establish the physical connection between the measured feature and the robot arm during measurement by connecting rigidly to the tool flange of the robot and by holding the test-pin. Furthermore, the measuring tool carries the cameras and LED light sources (together with their control modules) to enable robust image processing. The prototype of the tool was created with 3D printed components in a modular fashion, which facilitates the development process, later changes in the design, and also component replacement. The CAD model of the measurement tool is shown in Figure 3.

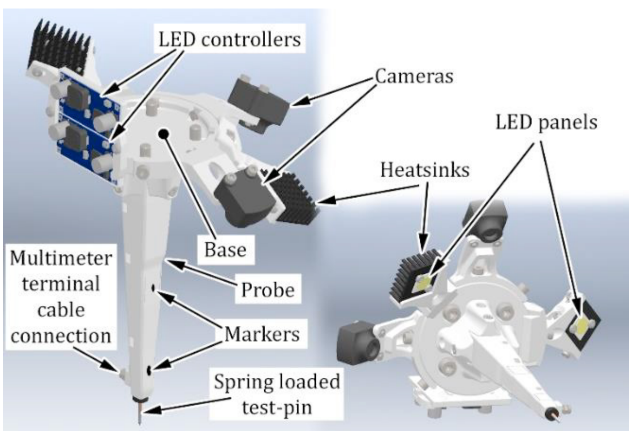

Figure 3. CAD model of the measurement tool.

The test-pin holding probe has an elongated shape so that the measurement tool can reach measurement points even in the close vicinity of higher components on the PCB (such as heatsinks). The test-pin is fixed in the probe with a screw, which also provides the electric contact for the crimped positive terminal cable of the measuring instrument. A spring-loaded pin (pogo pin probe) is used for the measurement, which makes robot control simpler and more robust. The robot TCP is configured so that it coincides with the tip of the pin. The test-pin can be easily replaced by unscrewing the fastener in case of damage or wear.

The cameras are fixed in such an angle that the camera axes intersect the axis of the test-pin under the tip of the pin. In this way, the camera images cover the measured feature as well as the probe. The probe contains two marker points per camera (shown in Figure 2), which indicate the axis of the test-pin.

The LED light sources are connected to the LED controllers and can be turned on and off during the visual servo method. Their role is to counteract the uncertainties of the environmental lighting conditions.

4.2 Visual servo technique

The visual feedback for the visual servoing probe test method is provided by a compound image processing algorithm using standard tools. The image processing is responsible for two main tasks, with the final goal being the calculation of the compensation vector for the servo technique. First, the marker points are detected on the camera images to determine the test-pin's axis from both viewpoints for the bi-directional error compensation. Second, the measured feature is identified on the camera images. For each measurement point and for each camera, a template pattern is selected, which serves as a reference image. When testing a particular measurement point on the PCB, the corresponding pattern is sought on each camera image in every servo iteration. The pixel position resulting in the highest correlation is selected as the target point of the compensation vector. Finally, the pixel distance is computed between the target point and the pin axis, perpendicular to the axis. This results in two separate compensation vectors – utilized as a displacement command for the robot – corresponding to two perpendicular directions in the plane parallel to the top PCB surface. The block diagram of the visual servo technique is shown in Figure 4. The sample template patterns are shown in Figure 5.

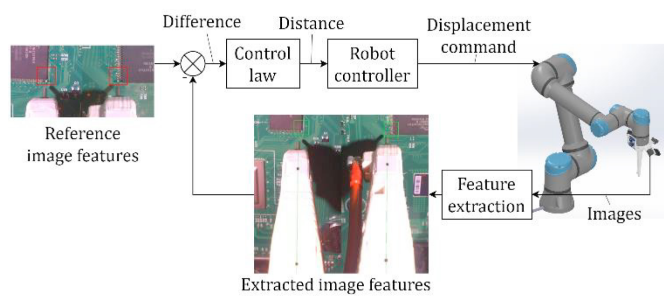

Figure 4. The block diagram of the visual servo technique.

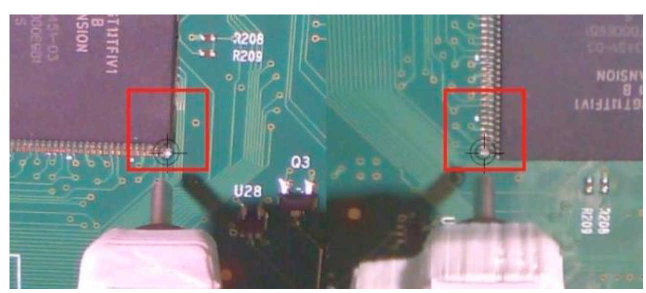

Figure 5. Template patterns for the measurement point U82.

Multiple termination conditions are defined for the servo method. First, a maximum initial error radius is assumed, i.e., if the robot TCP moves out of the circle defined by this radius around the starting point, the servo method is terminated (referred to as displacement error). This phenomenon can occur when the correlation between the template pattern and the camera image is weak (e.g., there is a significant visual deviation), and a false positive matching is found. Similarly, exceeding a specific force value measured on the TCP causes the method to stop, as the arising force most probably originates from a collision between the probe and the measured workpiece (referred to as force error). Furthermore, the servo method is terminated if the servo iteration does not converge quickly enough toward the acceptable alignment between the end-effector and the measured point (referred to as servo error). In all of the above error cases, the measurement – together with the feeding motion of the robot – is omitted in order to avoid any collision, damage or potential shorting of components. Otherwise, if no error is detected after the servo target is reached, the robot performs the measurement with the forward feeding motion, then moves back to the safety plane once the values are read from the measuring instrument.

4.3 Measurement profiles

In the absence of precise CAD drawings, template patterns and the corresponding starting robot TCP pose (position and orientation) are manually teached for each measurement point. The operator positions the robot with the probe above the feature to be measured (in the safety plane). At this point, images are captured with the LED panels turned on, and the feature is selected using a reticle on the zoomed in camera images with pixel accuracy. This is then stored with the robot TCP coordinates (recorded from the robot controller) and the operator attaches a label, measurement type (e.g., resistance or voltage) and reference electric parameters to the recorded measurement point. While on the safety plane, it is also possible to set a tilted robot approach direction (instead of a vertical one) by setting the probe tilt direction and angle, as well as the TCP orientation around the pin axis. These parameters are stored together with the measurement point.

By organizing different measurement points in a sequence, a measurement profile is formed, which can be assigned to a specific product type. During the testing of a PCB, using the product type identifier, the measurement profile can be automatically loaded and executed. Measurement profiles are set up based on the test specification by the operator expert. Measurement profiles can be extended, reduced or modified based on the acquired data and experience from previously tested PCBs of the same product type.

Teached-in measurement points need to be robust enough to handle most visual differences. It is the responsibility of the operator expert to consider lighting conditions and the PCB appearance and set the tilt and orientation of the probe in such a way that there are no significant shining spots or occlusions in the template pattern. Otherwise, the template may be unreliable when used with the same workpiece in slightly different lighting conditions or with a different workpiece of the same type. Geometric differences may lead to the need of an alternative, or an updated measurement profile to be compatible with the different PCB design.

5. EXPERIMENTS

To evaluate the performance of the proposed system, a series of experiments were performed. The test measurement cell includes a 6 DoF UR5e type robot arm equipped with the introduced measurement tool, a robot stand, as well as a worktable with three locator pins capable of locating the measured products. In addition, a control PC is present, which is responsible for the high-level control, interfacing the robot controller, measuring instrument, cameras and LED controllers. The measuring instrument is a HP 34401A multimeter controlled by the PC using serial connection. The measurement tool contains two IDS XS cameras, which are connected to the PC via USB ports. The positive terminal cable of the multimeter is connected to the test-pin on the measurement probe. The LED panels are connected to the LED controllers, which are attached to the robot controller's output ports. The cables for the listed connections are driven next to the robot arm links using cable holders to avoid tangling. The experimental cell is shown in Figure 6.

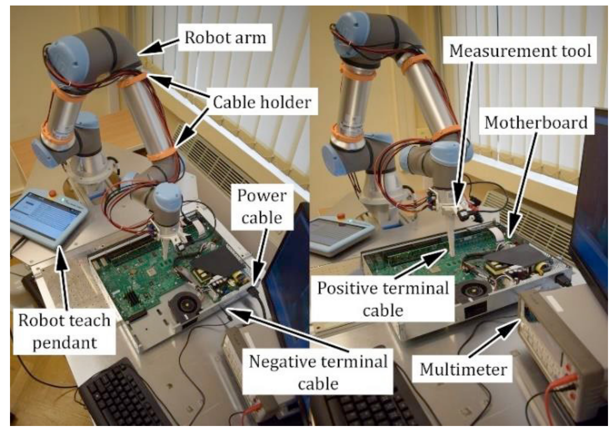

Figure 6. Experimental robotic measurement cell.

The cameras are set to a fixed focal length and their pixel resolution is 2592x1944. Camera to probe calibration was performed manually, however, no hand-eye calibration is necessary. The robot arm has 850 mm reach, allowing large variation in the size of the workpieces. For testing, a motherboard was selected with a size of 440x360 mm. The experiments focused on the robustness, time aspects and accuracy of the proposed visual servoing probe test method.

5.1 Experimental setup

Altogether 5 motherboards were tested, which are all of the same product type, but with different production dates, meaning there are differences between them. The deviations are mostly visual (the comparison of two particular workpieces is shown in Figure 1), the color tone of the boards is different, and the color of some mounted components vary (possibly due to different manufacturers). Moreover, one of the five motherboards contains an additional heatsink.

Each workpiece was measured with a common measurement profile that was set up on one of the motherboards. Before each measurement, the negative terminal cable of the multimeter is connected to the motherboard ground. Although automated measurement of resistance and voltage – or with the right measuring instrument even current and frequency – is a possibility, only resistance values were measured in these proof-of-concept experiments.

5.2 Experiments

A measurement profile of 6 measurement points was set up, containing two via holes (labeled R133 and Q3266), two IC legs (labeled C1519 and U82), a single coil leg (labeled 3R3) and a single solder joint (labeled Q3).

Each motherboard was tested in two lighting conditions, with and without the room lighting. Each time, the measurement profile was executed 25 times, which resulted in 5x2x25=250 measurement cycles. Each cycle contained the aforementioned 6 measurement points, which altogether resulted in the execution of 6x250=1500 visual servoing probe test cycles. At the beginning of each servo cycle, a disturbance is considered to simulate the accumulated position error of the board. The disturbance values are randomly sampled from a ± 2 mm range for the x and y direction, and from a ± 0.2° range for the orientation around the axis perpendicular to the board surface and intersecting the TCP. The sampled values were then applied on the robot starting TCP pose.

In each visual servoing probe test cycle, the following data was stored: the value measured by the multimeter, the number of servo iterations, the time of the servoing (T_{servo}), the displacement, force, servo and contact errors, as well as the camera images at the time the contact is established between the test-pin and the measured point (samples shown in Figure 7). The experiment results are shown in Table 1.

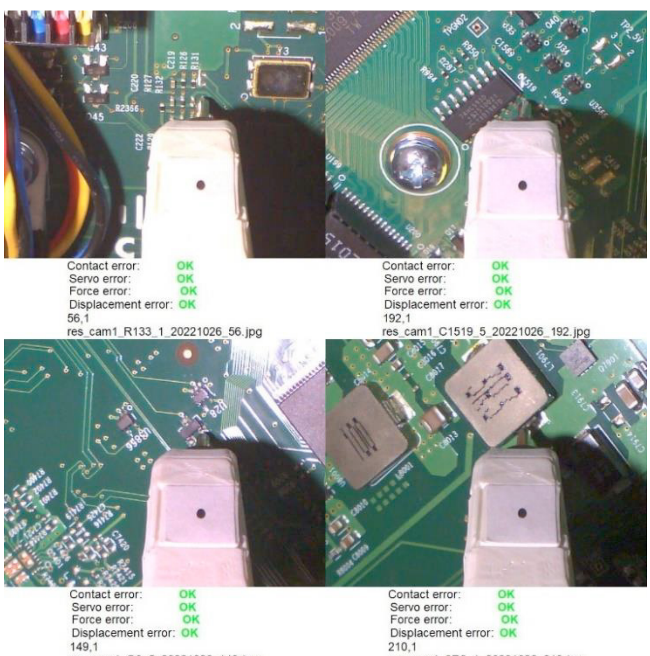

Figure 7. Sample camera images at the time of physical contact for measurement points R133, C1519, Q3 and 3R3.

Table 1. Experiment results

Measured feature label	Feature type	Feature size [mm]	Tilted robot pose	Disp. error	Force error	True force error	Servo error	Contact error	Successful measurement	Successful measurement [%]	Mean servo iteration number	T_{servo} mean [s]
R133	Via hole	⌀0.2	No	0	1	0	0	0	249	99.6	10.30	8.74
Q3266	Via hole	⌀0.2	Yes	0	0	0	0	4	246	98.4	10.25	8.54
C1519	IC leg	0.5x1	No	0	0	0	0	0	250	100.0	10.31	8.64
U82	IC leg	0.25x1.2	No	0	0	0	0	0	250	100.0	10.18	8.51
3R3	Coil leg	3x2	Yes	0	0	0	0	0	250	100.0	10.88	8.89
Q3	Soldering	0.85x0.85	Yes	0	0	0	0	0	250	100.0	10.57	8.80
Overall	-	-	-	0	1	0	0	4	1495	99.7	10.41	8.69

In case of R133, one force error case occurred, but after checking the recorded images at the end of the servo cycle, it was clarified to be a false force error case, as no physical contact was observable between any components. This phenomenon is probably due to robot acceleration resulting in a higher sensed force than the used sensitive force limit. The other four error cases occurred in the case of the Q3266 measurement point. Here, the contact between the test-pin and the via hole was not properly established, and the multimeter measured 10^{39} Ω resistance, i.e., no electric contact was formed. These errors may have been caused by positioning failure due to visual deviations, different coatings on the workpieces needing higher testing force, or imprecise teaching (template pattern selection). No other error cases occurred in the experiments, and thus the overall success rate of the measurements was 1495/1500=99.7%.

6. WORK IN PROGRESS

The achieved success rate is promising, especially considering the variations in the products and lighting conditions. However, there are additional developments, which can further improve the applicability of the approach.

One goal is to elaborate a homography-based method for fixtureless measurement, capable of overcoming tens of millimeters error in the positioning. Also, the robustness to visual deviations is being improved by allowing multiple template patterns for a single measurement point with automatic selection of the one resulting in better correlation.

On the efficiency side, the cycle time is being reduced in multiple ways. As the preparation of the measurement cycles is manual, a workpiece buffer is going to be established by having multiple measurement stations within the robot's workspace. Additionally, sequence planning is being introduced to automatically find the time optimal sequence of measurement points within a measurement profile.

Lastly, automatic calibration methods are developed to compensate for probe wear, as well as probe and measurement tool replacement.

7. CONCLUSION AND FUTURE WORK

In this paper, a novel visual servoing probe test method and corresponding measurement tool was presented for preparing and executing flexible PCB measurement tasks. The presented method does not require precise information about the geometry of the PCB (e.g., CAD model), measurement profiles can be set up with simple point teaching using the robot and the corresponding feature to be measured. The proof-of-concept experiments showed that the overall accuracy of the system is 99.7% based on a total of 1500 measurements with 6 measurement features, 5 particular PCBs of the same product type and 2 different lighting conditions.

The research is still work in progress, the system will be further updated with an initial error estimation method for fixtureless measurement, multiple template patterns per measurement point to improve robustness, as well as automated tool calibration methods. The introduction of machine learning is a possibility for future work for success evaluation, estimation of success rate based on teaching, and finding rules for successful teaching for the operator. Furthermore, the extension of the system with a second robot for two-probe measurements is a potential research direction. This would increase the applicability of the system by allowing differential measuring types.

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