
The U.S. Department of the Treasury’s Bureau of Engraving and Printing (BEP) is responsible for producing all of the currency for the world’s largest economy. From the paper on which the currency is printed to its sheer output of approximately 37 million notes each day, nearly every aspect of BEP’s design and printing process is distinctive.

Many of the BEP’s quality assurance needs are unique as well. Like all printers, the BEP must verify that its printed materials are clear and accurate. However, the BEP also needs to ensure that various security measures are in place to help deter counterfeiting and to allow the government to account for all bank notes. To help meet these demanding requirements, the BEP converted several of its inspection stations from human operators spot checking currency to automated visual inspection of each note.

Banking on Machine Vision

The Bureau of Engraving & Printing identified several areas of the bank note printing and production process that would benefit from automated visual inspection. To help ensure security, reduce variability and maintain BEP’s high print standards on each note, the BEP competed and selected the Sherlock machine vision software application for the development of three machine vision systems: automated inspection systems for printing plate quality assurance, automation of measuring finished notes for print registration consistency, and on-line measurement of a quality and security feature on newly printed bills.

Printing Plate Quality Assurance

In order to reduce or eliminate inconsistencies associated with physical note size and the location of engraved images on the chrome intaglio printing plates on which the currency is printed, the BEP’s Production Engineering group developed a Plate Measurement Device (PMD) (Figure 1).

The PMD uses state-of-the-art positioning technology and machine vision to automatically measure the layout pattern of the security features on these plates. The engraved artwork and registration marks are gauged before production to verify plate accuracy—which is essential for precise print registration—and afterwards so that any distortion caused by prolonged intaglio printing is identified.

Figure 2. The operator controls the PMD vision system using a customized graphical interface via keyboard and mouse. A 21-inch color monitor displays a live image of the currency plate being inspected.

Rather than implementing a pre-built, non-customized system that would be more costly to implement and maintain, the team developed the PMD’s machine vision inspection system using a variety of advanced, off-the-shelf opto-electronic components. A frame grabber integrated within the host PC captures images from a 1K x 1K monochrome camera. Using a precision lens with a 0.5” field of view, the camera achieves a measurement tolerance of +/- 0.001.” In addition to capturing images for analysis, the frame grabber provides the digital Input/Output (I/O) that is used to monitor manual switch settings and safety sensors on the PMD. The operator controls the vision system using a customized graphical interface via keyboard and mouse, and a 21” color monitor displays a live image of the currency plate being inspected (Figure 2).

Since the polished chrome plates are shaped to follow a four-plate printing cylinder radius, obtaining a quality, high-resolution image was one of the major challenges that the team faced. They solved the problem by using an LED-based, dark field illuminator in conjunction with a megapixel camera, making the engraving appear clear and well-defined for the machine vision software’s calipers to perform measurement functions with minimal pre-processing of the image. After the PMD captures all pertinent plate data, analysis is performed using machine vision software and an object oriented program.
language, and then all data is automatically saved to a network database. The analysis tool can also compare the current plate to a “Golden Plate” (Figure 3, which can either be a mathematical composite of the target plate or a plate that was previously measured. When comparing the current plate to the golden plate, the operator can specify a tolerance. The monitor displays measurements outside the tolerance in red and an acceptable reading in green. The golden comparison provides the operator with immediate “Go/No Go” feedback, while the networked data is used offline to detect process trends so that any recurring positioning problems can be identified quickly and remedied. The machine vision software is seamlessly integrated with the object oriented program interface, which enables users of all computer skill levels to successfully analyze images.

**Plate Comparison Data**

Comparing Plates: $20 Front 472-38-38 to $20 Front 472-45-45

X tolerance: .06

Y tolerance: .06

Features Compared: (Step and Repeat)

All measurements in millimeters

![Plate Comparison Data](image)

Figure 3. Analysis on plate data is performed using machine vision software and object-oriented programming. The analysis tool can also compare the current plate to a “Golden Plate,” which can either be a mathematical composite of the target plate or a plate that was previously measured and accepted.

The PMD machine vision system has been operating successfully eight hours a day, five days a week for three years, and has proven to be an integral part of the quality assurance and process controls associated with printing United States currency.

**Measuring Finished Federal Reserve Notes for Print Registration Consistency**

All finished banknotes are targeted to be the same size and are printed 32 per sheet. Although each sheet is electronically inspected on the printing press and again before banknote numbering, the BEP did not have a reliable way of identifying finished banknote feature registration discrepancies that occur as a result of accumulated subtle variations with the many print phases and trim operations associated with currency production. Without this information, the BEP was unable to quantify its process capabilities or to measure improvements in banknote quality. Therefore, the Production Engineering group developed a vision-based note measurement system that automatically measures and records 27 note registration features (137 data points) on each cut bill. These include substrate size, intaglio print size and position (on both sides) and position of the seals and serial numbers. Measuring banknotes in reflected light is quite challenging, as the intaglio printing process is somewhat variable by nature and finding print edges consistently on the fine engraved artwork is very difficult.

An image-based inspection system proved to be a successful approach, which provided enough flexibility to accommodate multiple banknote designs (Image 4). Each note measurement station consists of a vacuum fixture to hold and position the banknote, three digital cameras, a microprocessor-controlled light source, a Continuously Diffuse Illuminator (CDI), a PC equipped with two frame grabbers, and two machine vision software packages that co-exist for image analysis. After each note is precisely positioned beneath the camera, images of the front and back of each note are taken and transferred to the frame grabber. Each captured image is then analyzed by both machine vision applications for OCR and caliper measurement. The software’s landmarking tools are also used to account for variations in trim and print, and to compensate for notes incorrectly oriented on the vacuum table. Using grayscale edge detection, the machine vision software application is able to measure pixels and sub-pixels repeatably for precision within +/- .2mm. This was a crucial aspect of this solution’s success, as many of the fine line features printed on banknotes are smaller than the camera’s pixel resolution.

The Production Engineering team developed a software application that provides an easy-to-use graphical interface, scales pixel measurements to millimeters, enforces data integrity, and stores the resulting measurements in a spreadsheet-compatible database. The BEP provides this data to its customers and partners to inform them about expected process variations.

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The technology has opened a new window through which the BEP can evaluate product quality. Using this vision system, members of the Production Engineering group are currently able to quantify the registration variability in the BEP’s banknotes to within a half-millimeter granularity. As they leverage their experience with this technology, the group anticipates it will have the ability to build the tools needed to measure even finer reductions in banknote variability.

Semi-Convert Inspection to Measure Quality and Security Features

With ongoing quality considerations and the increasing need for security features to help deter counterfeiting, the BEP’s Production Engineering team also developed an automated inspection system to examine a semi-covert, machine-readable feature on each banknote. This feature is created by applying inks in denomination-specific patterns in precise locations throughout each printed sheet.

The BEP had used human inspectors for this application, but, with 8,000-10,000 sheets of 32 banknotes coming off the presses each hour, only a very small percentage of sheets were inspected, and with less reliability than the BEP knew it could get from an online, automated system. Building an inspection system for this application was no easy task, as it is used in a harsh pressroom environment inside a high-speed printing press that applies 80 tons of pressure to each sheet. This process creates floor-shaking vibrations that make capturing a quality image very challenging.

The Production Engineering group’s inspection system starts with an 8-bit monochrome tethered head camera that provides increased sensitivity and low light imaging capabilities. In addition to capturing images from the camera, a frame grabber provides digital I/O capabilities that activate a light bar and voice module. These indicators provide operators with feedback about each sheet (both printed and substrate areas) so that any problems can be remedied quickly.

The system incorporates off-the-shelf machine vision software for image analysis capabilities. Using an object oriented program language integrated into the machine vision software application, the Production Engineering group also wrote several custom algorithms to further enhance the system’s ability to capture sharp, high-quality images under such demanding conditions.

Over the past four years, the system has been operating 24 hours a day for 5-7 days each week to perform 100% inspections at a minimum of 2.4 sheets per second.

Short and Long-Term Payoffs

The Production Engineering group evaluated several products before choosing its machine vision software package, the decision was based on the ease of developing inspection algorithms coupled with the ability to create an object oriented program language front end that can be used easily by operators with varying degrees of computer experience. Recent additions to the software application—such as callback capability and image mapping, and improved Optical Character Recognition (OCR) and Optical Character Verification (OCV) add-ons—help make this package a good fit for both the BEP’s developers and users.

In each of the three applications for which they have implemented machine vision software solutions, the BEP has benefited from improved quality assurance, better information about its processes that allow any needed action to be taken quickly and reduced human inspection costs, along with increased inspection accuracy.

The Production Engineering team is currently making improvements to the existing systems to gain even greater reductions in print variability and to inspect ever-more sophisticated security features. The group continually makes improvements to its processes for quality assurance and security purposes, and machine vision plays an important role in this regard. The data received from these inspection systems also will be instrumental in implementing future security or design changes.

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