Making Money with Machine Vision

Mike Muehlemann
Illumination Technologies, Inc.

Although we seldom think of it as a product, printed currency is a manufactured good that must meet stringent product specifications, have high quality standards, and must meet ever-increasing pressures for reduced unit cost. The product is manufactured in high volumes, distributed to a host of demanding customers, and is constrained by the same set of fundamental production principles as are most other conventional manufactured goods.

The unending drive for tighter specifications, higher quality, improved yield and reduced unit cost make machine vision inspection technologies every bit as beneficial to currency manufacturing as they are to the manufacture of semiconductor and electronic goods. Over the past decade, machine vision technologies have demonstrated that they can deliver higher quality, at the same time delivering higher yields and reduced unit costs for many diversified industries.

Manufacturing money is no exception. Similar to other high volume products, printed currency has a great number of highly critical specifications, many of them related to security and counterfeit issues. And similar to so many diversified manufacturing operations, machine vision tools prove themselves invaluable in improving quality while simultaneously reducing unit manufacturing costs.

The US Treasury Department's Bureau of Engraving and Printing (BEP) designs, prints, and finishes a large variety of security products including Federal Reserve notes, U.S. Postage stamps, Treasury securities, identification cards, naturalization certificates, and other special security documents. Since 1913, the BEP's primary customer has been the Federal Reserve System and currency the primary product. American currency is manufactured using distinctive cotton paper and unique inks as raw

Figure 1: The Bureau of Engraving and Printing produces all US currency on a total of 24 presses located in two different locations

materials, from which is produced a highly specialized finished good with very tight quality control standards. As with any manufacturer, the BEP feels the same pressures to develop new and improved products, lower operating costs, increase performance and yields, increase throughputs, and reduce delivery times.

Worldwide, currency manufacturing has not been immune to outsourcing. In some countries, the job of printing and inspecting currencies is outsourced to private companies that have become very technically adept and competitively priced at this task. In fact, one of the largest worldwide manufacturers of currency is a privately held for profit corporation.

With the look and feel of an aggressive private enterprise, the BEP has implemented next generation vision systems that have positioned it as a world class force in the security printing market. The Bureau of Engraving and Printing was originally established in 1862, in the basement of the Treasury building where 6 employees sealed $1 and $2 banknotes by hand that had been printed by private bank note companies. Today there are approximately 2,500 employees who work out of two buildings in Washington, D.C. and a new facility located in Fort Worth, Texas. Currently the BEP prints an average of 8 billion currency notes per year.

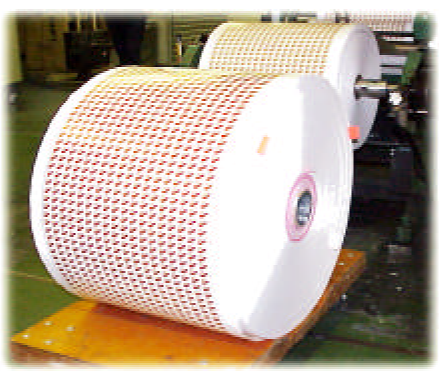

Figure 2: The BEP also produces about 12 billion postage stamps per year (about 20% of all US stamps)

For the past eight years the BEP has implemented machine vision technologies to inspect currency for 10 or more overt features, and several more covert features designed to incorporate anti-counterfeiting features within the product. Features include color-shifting inks, a watermark, microprinting, a security thread and other features that are difficult to copy. Although all denominations of the new currency have these security features, the number of features vary according to denomination. While the $20, $50 and $100 notes have a full package of features, lower denominations have fewer and less sophisticated features.

A larger, slightly off-center portrait is the most noticeable visual change in the newer style currency (see Figure 3). The larger portrait incorporates more detail, making it easier to recognize and more difficult to counterfeit. Moving the portrait away from the center, the area of highest wear, extends the note's lifetime. Another reason that the portraits are shifted off center is to provide room for the watermark (4), which is created during the papermaking process and is difficult for counterfeiters to reproduce. The watermark depicts the same historical figure as the engraved portrait.

Other security measures include fine-line printing (2,8), which is difficult to replicate accurately on scanning equipment or by other means of printing. There are also color shifting inks (5) employed that change from green to black when viewed from different angles. This feature is used in the numeral in the lower right-hand corner of the note front.

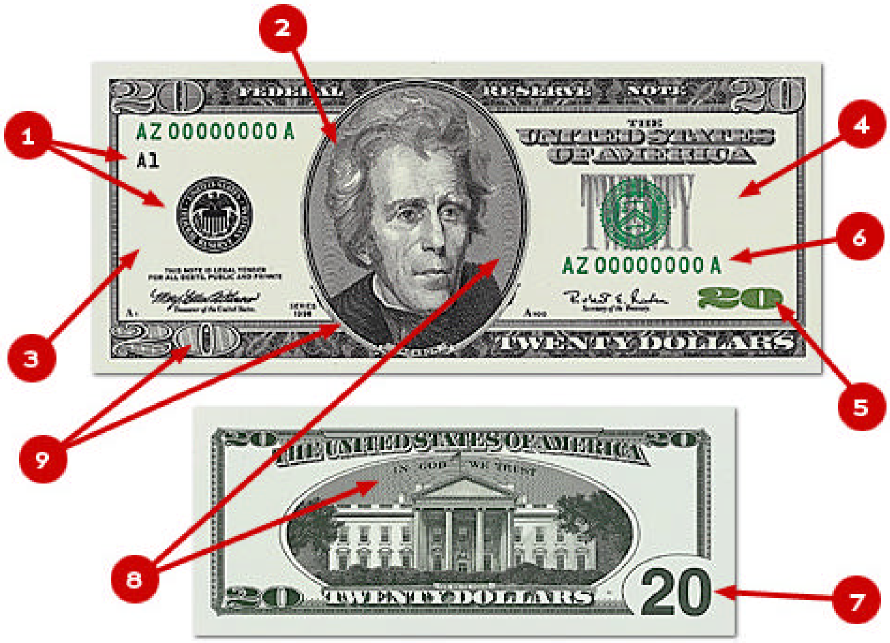

Figure 3: The new currency features a variety of new security measures including a hidden watermark portrait (4), fluorescent security threads (3), and color changing inks (5)

There are also fluorescent security threads (3), which have a unique position for each denomination. In the $20 note, the thread glows green when illuminated under ultraviolet light; in the $50 note it glows yellow; and in the $100 note it glows red. The denomination of the note is also printed on the thread; for example, "USA TWENTY" and a flag are repeated along the thread in the $20 note. There are also other microprinting techniques (5,9) used throughout the notes to further deter counterfeit activities. While these measures help thwart counterfeiting activities, they serve to increase the difficulty associated with inspection.

<u>Security Printing Markets and Counterfeiting</u>

With the advent and proliferation of personal computers, digital scanners and color printers, the market demands placed on the security printing industry have increased exponentially. Digital Counterfeiting (Digifeiting) activities have increased at an alarming rate, with estimates of over 60,000 new incidents per month. The quality of these counterfeiting attempts improves with every new wave of computer peripherals.

Prior to 1996, the design and manufacture of U.S. currency had not changed significantly in over 70 years. As the most international of all currencies, demands for more counterfeit deterrence in currency has increased dramatically over the past two decades. The recent changes to the U.S. notes (except the $1 note) have been phased in over the last 5 years, the final phase complete with the introduction of the $5 and $10 earlier this year. The next phase of unspecified changes is anticipated shortly, and another wave is expected around the end of the decade .

The newly designed notes ($100, $50, $20, $10, $5) are most readily identified by the larger portraits which are now offset from the center. One of the most interesting new security measures is the introduction of watermarks of the presidential portraits, (see Figure 4). The watermark is a non-printed security feature located to the right of the main portrait, and can only be seen under appropriate backlighting conditions. It is a specially embedded process within the cotton and linen fiber based paper, and is very difficult to emulate with any type of printing process. As with all the security features, machine vision tools are used to inspect the quality of this embedded watermark.

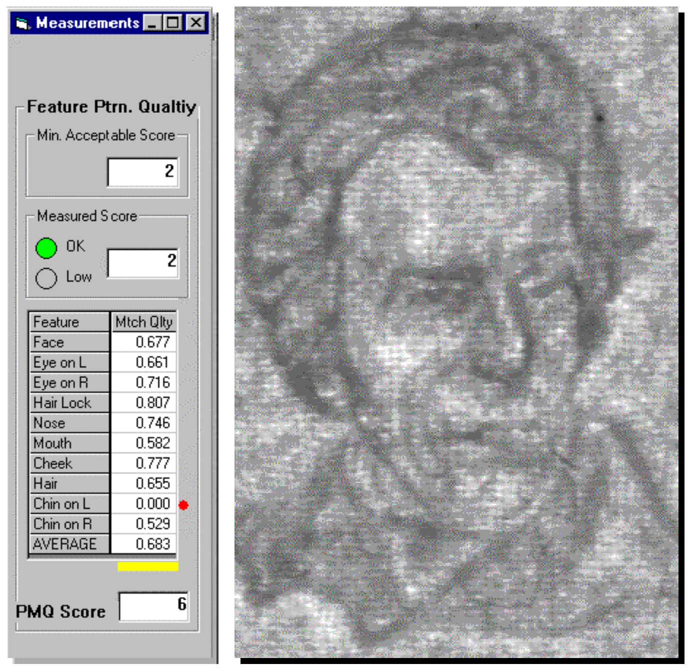

Figure 4: The hidden watermark, to the right of the main portrait, is only visible by backlighting the bill, making it difficult to duplicate via printing methods.

Several changes have been made on the new notes; changes that must now be carefully inspected on 100% of the currency being produced. “Rapidly changing market conditions have put us in a 5 - 7 year design cycle aimed at keeping ahead of counterfeiters and maintaining international confidence in our product”, according to Mark Poulsen, Technology Development Group Inspection Leader at the BEP. **“**From a manufacturing standpoint, we prefer that our product continues to be in demand internationally. With the advent of the “Euro”, currency users now have a choice and we must continue providing a world class product”, says Poulsen. All indicators are that consumers should expect to see a much more aggressive timeline for currency evolution than we have seen over the past century.

In addition to competitive pressures, the market place for many U.S. notes has also changed. One hundred years ago currency was produced specifically to have a look and feel that was targeted exclusively at human users. The specialized intaglio (pronounced "in-TAL-ee-oh") printing was perfected to give the printing that raised feel that we still subconsciously notice today. The intaglio printing process, converse to normal print processes, utilizes engraved printing plates, which are covered with ink that flows into the crevices of the engraving. The surface of each plate is then wiped clean, allowing ink to remain in the grooves of the plates. Each cotton fiber paper sheet is then fed between rollers under extreme pressures (almost 20 tons per roll). This then forces the paper into the finely recessed lines of the printing plate where it picks up the ink. The resulting printed impression is slightly raised, giving the notes their three-dimensional feel. This special process is run on high-speed, sheet-fed rotary presses that are capable of printing over 8,000 sheets per hour (32 notes per sheet). Currently the BEP operates a total of 24 high-speed currency presses within their two facilities.

“In the 21st century, we see some of the long standing assumptions about currency changing”, according to Don Bayer, Technology Group Manager at the BEP. “Paper currency is now being accepted by an ever increasing array of automated vending and dispensing machines. In these applications, the look and feel of the currency is much less important, but the exact nature of the printing, and the registration of characters and graphics is highly critical”, says Bayer. This portion of the market has become large enough to dissuade changing of the $1 to the new design because of the significant cost associated with updating the installed base of note readers.

“The end result of all of these market changes is that the next generation currency continually needs to push the envelope in terms of design complexity, security measures, repeatability, reproductive accuracy, and registration”, says Poulsen. “With all this increased complexity, it really drives our degree of difficulty because we have to be able to inspect the finished product with extreme accuracy, and at high speed - and we don’t have an open check book to do it with either. Efficiency and customer satisfaction are business rules that absolutely apply to this facility. It is very easy for our customers to compare security-printing prices with many other countries, and quality mistakes are no longer merely numismatic collectors items. $64 billion a year in cash transactions are handled via machine vendors, a running print defect can become a major financial burden to this large and growing industry as well as prevent you from getting that soft drink or mass transit pass because the vending machine will not accept your cash.” says Poulsen.

One of the ways the BEP is ensuring their ability to deliver world-class currency today, and well into the future, is through the successful implementation of new machine vision inspection tools. These automation tools perform the critical function of inspecting the currency product at many stages throughout the manufacturing process. In addition to the in-house development of one of the world's most sophisticated color inspection prototype systems, other specialized machine vision based systems have been critical to the groups overall success. For example, machine vision tools have been instrumental in controlling key pre-production stages during the manufacture of the plates themselves, and again in post production characterization, including long-term quantitative stability studies.

"Through the development of several sophisticated machine vision tools we discovered that very small changes in the plate manufacturing process had a big impact on final registration issues, a result we did not expect", says Max Grimsley, Technology Group member at the BEP. "Without these highly accurate machine vision tools, we would never have been able to isolate the underlying causes, and make the requisite quantitative changes necessary to meet our registration issues with the kind of high yields we are capable of today. Our entire plate manufacturing process is now quality assured using machine vision tools that check the critical note locations (position is denomination dependent), and verify that each plate's alignment points are exactly where they are supposed to be. Both measurements are accurate to within 0.001". The results will save thousands of dollars and countless hours during the setup operation, and have greatly reduced the back and forth between our Plate-Printers and our Engraving division", says Grimsley.

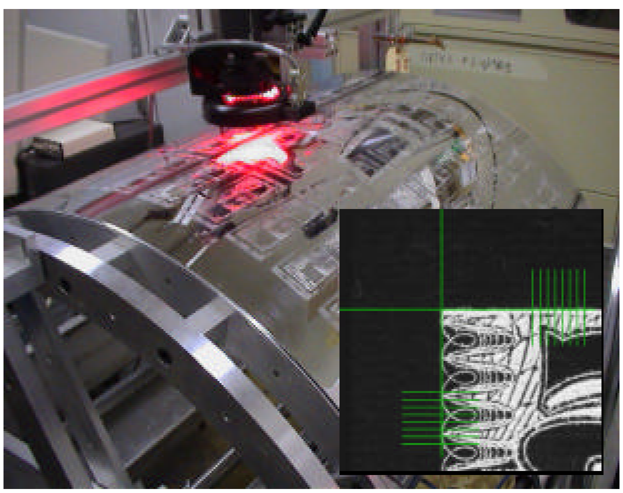

Figure 5: Plate Inspection System delivers accurate information about plate placement. Insert in lower right corner shows darkfield image obtained under high magnification

The Plate Measurement Device (see Figure 5) analyzes each of the plates before they are installed in the presses. An LED Dual Mode Illuminator (DML) provides the uniformity and high contrast necessary to accurately measure the small engraved features of each plate. The image is acquired by an area matrix CCD camera, and the motion control system accurately locates each plate's fiducial position on a radius to within 5 microns. The lifetime of each plate is about 1,000,000 sheets, which translates to about 500 hours of production run time before the plates must be replaced.

"The Plate Measurement Device has been instrumental in reducing downtime, and ensuring that accurate and perfect plates are installed so that minimal time is wasted producing faulty currency or having to perform secondary setups," according to James Hess Technology Development Group member and primary integrator of this system.

“In retrospect, a post-production machine vision study actually turned out to be the real starting point”, according to Ken Rankin, Technology Development Group Inspection Leader. “Before we could even implement the Plate Measurement Device , we had to create statistics for the product we have been producing for the last 70 years, and then see how these parameters were changing out in the field. Strange as it may seem, we had little knowledge about many key registration issues with respect to post-production because it had never been much of an issue in the past. We not only needed to find out how the product varied at the end of the production lines, but we needed to know how it varied over its field lifetime”, said Rankin .

Like all products, currency has a limited useful lifetime. The lifetime of the currency varies as a function of denomination, with the $1 having an average service life of only about 22 months, while the $100 note has the longest average service life at nearly 9 years. At any given time, there is quite a bit of currency in circulation. As of July 2000, there was $540 trillion in total worldwide currency circulation, and more than 2/3 of that value was in the $100 denomination. While all this currency is in circulation, it is being exposed to a wide range of environmental challenges, from temperature extremes to washing machines, all of which have an effect on the ultimate long term stability.

Figure 6: Note Measurement System provides highly accurate data on currency stability and registration and is instrumental in understanding the intricacies of the manufacturing process

In order to establish the stability of the different notes over a period of time, the Technology Development Group at the BEP developed a key piece of machine vision technology named the Note Measurement Station. This system generates a database of new and used notes with detailed and highly precise measurements on a variety of repeatability and stability parameters. A highly uniform Diffuse Ring Illuminator (DRI) provides high contrast images to three high resolution area matrix cameras. The field of view (FOV) is calibrated using highly accurate targets and then the images from a large number of notes were acquired, and key gauging data was extracted and stored in a database for analysis.

“Until we took the time to do that, we had not quantified how good we had been in the past regarding registration of key features, or how stable some of the other parameters were as a function of time and field use,” said Rankin. “To make matters even more interesting, once we had all the data, proprietary concerns from many of the key vending industry players precluded establishing an industry standard set of specifications. However, once we understood what the variability of these parameters had been historically, we were able to identify changes to our manufacturing process that will ensure much tighter controls than was ever thought possible before", he said.

Perhaps even more advantageous, was the fact that the data highlighted key aspects of the manufacturing process itself that were never really understood before. Certain trends in the data suggested that many of the registration issues were derived from process control issues that were inherent in the intaglio printing process. The information gained from the Note Measurement Station was instrumental in providing insight into the manufacture of the plates used to print the currency, and in defining the requirements for the Plate Measurement Device.

An important step in the manufacturing process is to analyze the printed sheet for all of the security features to ensure that each note is perfect. The final inspection of the sheets themselves is a complicated and necessary task, and machine vision plays a major role in this phase of the process as well. As the number and complexity of security features increases - so does the difficulty of the machine vision inspection task. Vision system technologies have been inspecting currencies at the BEP for more than eight years, but with the recent and anticipated changes in the US currencies design and printing, some of these existing machine vision inspection tools have become outdated.

"Some of the existing machine vision tools are not well suited for the future because they lack the scalability required to address these new security features as they are introduced", says Poulsen. Applying a different model to address this issue is proving to be an efficient and effective way to meet some of these requirements. Using Commercial Off The Shelf (COTS) components to the greatest extent possible and in-house integration, with specialized assistance from industry experts when pertinent, the BEP has successfully developed several specialized systems quickly and cost effectively. A next generation, high resolution, large format, high speed color print inspection prototype is currently in the development phase and this cutting edge system is also a good fit for the in-house/COTS model. Even

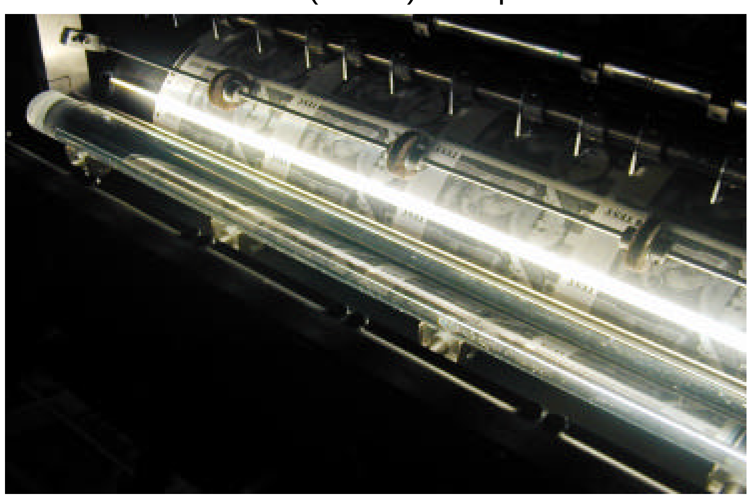

Figure 7: Color Web Inspection System inspects at high magnification and high speed. Automated camera and lighting controls deliver optimum performance.

though the presses are sheet type presses (a brief experimental phase using web presses in the early nineties proved to have insufficient yield), this prototype is web based. This system utilizes three-chip color linescan cameras and high intensity fiberoptic lightline lighting systems with cylindrical collimating optics. Because this is a color based system, the spectral properties of the illumination system are critical to optimizing performance and ensuring accurate results, and the high-speed aspects drive the illumination systems to demanding intensity and uniformity levels.

"The advantage of these lighting systems is that they provide extremely good color rendering, great calibration control, and easy to use diagnostic tools", according to Poulsen. "We are able to have finer resolution, run at faster speeds, and have more control over the spectral variations in our product. We also have the flexibility to adapt to new currency design changes quickly and cost effectively. Currently we utilize specific hardware and software that addresses the functionality that is needed today to inspect in reflected front lighting modes as well as in transmissive backlighting modes. This system also provides future flexibility to integrate the many inspection systems for covert security features. Integral to the successful operation of these systems, we have also developed completely automatic camera and lighting calibration algorithms that help us optimize the image quality for these diversified security features, reduce system downtime, and increase the overall system performance. Critical to the success of this system has been dedicated in-house support from the executive level, production level, engineering group, machine shop, and production support staff. Great components, great technical support and innovative help from some of the best vendors the machine vision industry has to offer is setting a new benchmark for the in-house/COTS integration model. We envision this system helping to position the BEP as a technology leader in the high end security printing business for decades to come", he said.

Conclusion

The pace of technology has irreversibly changed the landscape for currency design and production. If current trends in other developed countries are any indication, currency will continue to become more complex and more colorful. The continued move to multicolored currencies adds many additional dimensions to the fight against counterfeits. It also places significant demands on the machine vision technologies that must be used to inspect the end product. Manufacturers of this most interesting product will be forced to stay one step ahead of their competitors, during a period where product design cycles will continue to decrease. They will be pushed to manufacture their product at increasing speeds, with higher resolutions, increased color depth and with higher throughput and yields than ever before. Organizations that have invested in these kinds of world class machine vision inspection systems should be "*makin' money*" well into the next century.