Smart Camera Mimics Humans Decision Making Process in a Vial Crimp Quality Automated Inspection Process

Jorge R. Delgado
Master of Engineering in Manufacturing Engineering
José A. Pesante Santana, Ph.D.
Industrial Engineering Department
Polytechnic University of Puerto Rico

Abstract *— Crimp quality is an important attribute in the vial filling process. It protects the sterility of the product from manufacturing until it is dispensed. A pharmaceutical company performed a Failure Mode and Effect Analysis to identify potential risks in its existing capping operation. Due to the severity of crimp failures, even risks with low occurrence have a moderate to high risk level, unless detectability of such defects is certain. Introducing a manual inspection process in parallel with the crimp process is not practical for high volume products. PC-Based vision systems are complex, expensive and require floor space, rarely available in an existing operation. Advances in smart cameras have allowed the development of a vision system capable of mimicking the human decision making process in discriminating between good and bad crimps at low cost with minimum impact to the operation.*

Key Terms *— Automatic Inspection, Crimp Quality, Smart Camera, Vision System.*

INTRODUCTION

A large biopharmaceutical company manufactures drugs in sterile dosage form packed in glass vials and closed with a rubber stopper fixed in place by an aluminum cap. A Failure Mode and Effect Analysis (FMEA) performed in an existing filling line revealed several medium to critical risks associated to the cap/crimp process. Scores in the FMEA were high mainly due to the severity of crimp defects, which might impact product sterility, and low detectability at the filling lines, which relied on sampling inspections.

Increasing the detection capability of crimp defects would mitigate all risks identified. Manual inspection is not practical due to the high volume and throughput of the line. A PC-Based Automated Vision System requires space that is not available at the existing line.

New generations of smart cameras have significantly increased the capability of these devices in performing different type of inspections. Crimp quality inspections are difficult because a pass/fail criterion cannot be established by a specific measurement or an absent/present attribute.

To mitigate the risks identified in the FMEA, a vial crimp quality automated inspection system was develop, using a smart camera. The system inspects vials for crimp quality prior to the trayloading operation, refer to Figure 1. The use of the smart camera allowed the implementation of the new system without impacting the existing operation or requiring additional floor space.

Figure 1
Crimp Quality Automated Inspection System

The system integrates different inspection tools evaluating multiple attributes of the inspected parts, and logic routines to discriminate between good parts and parts with potential impact to product quality.

BACKGROUND

Most biotechnology drug products are administered by the parenteral route, because of bioavailability and stability reasons. They are introduced in a manner that circumvents the body's most protective barriers, the skin and mucous membranes, and, therefore, must be "free" of biological contamination. The container closure system protects the sterility of the product. One of the most common closure systems for parenteral products is the combination of glass vial, rubber stoppers and aluminum cap. According to the Food and Drug Administration, the vial cap provides the final closure element of a sealed vial [1]. The cap on the vial protects the stopper from external damage, while firmly holding the stopper in the fully seated, sealed position.

Cap crimp quality inspections are performed manually, or by PC-Based automated vision systems. Inspections are challenging because crimp quality is not a criteria that can be established by a particular measurement, but rather by the result of different attributes inspected. Manual inspections are slow and not practical for high volume products. PC-Based systems are expensive and require considerable floor space and have a complex configuration, as depicted in Figure 2.

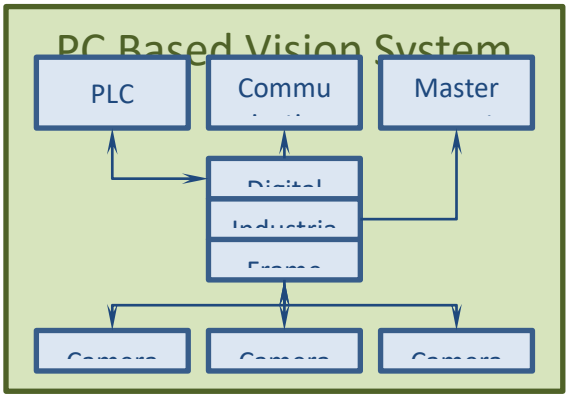

Figure 2
PC Based Machine Vision System Configuration

In both cases, manual and PC-Based inspections are not in-line with the filling operation due to space constraints and impact to throughput. Filling operations usually rely on in-process inspections to detect crimp defects. If there is a systemic condition leading to crimp defects the in-process inspection will have a good chance to detect it, but if there is an isolated condition, an in-process inspection have little chance to detect it.

Advances in smart camera vision systems allows the implementation of a compact, inexpensive system capable of effectively mimicking the human decision making process to discriminate between vials with acceptable crimp quality and vials with the potential to impact product quality.

Smart camera vision systems combine low-cost distributed processing with high-speed networking. They generally have one or two processors per camera, performing the image acquisition and image processing operations [2]. Most smart camera vision systems provide a configurable environment that's easier to use, integrate, and maintain. A simplified functional structure of a typical smart camera illustrated in Figure 3 shows how simple and compact the devices are [3].

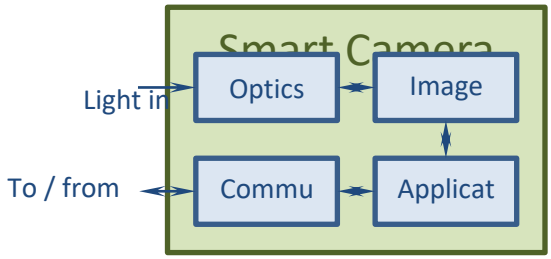

Figure 3
Smart Camera Basic Structure

Smart Cameras technology is already been applied in a number of industries. Their application is focused in narrow defined scopes; however, the inspection capability of smart cameras is growing continuously. Companies like Omron, Cognex and Keyence offer smart camera vision systems, which can be adapted to detect crimp defects with a deep understanding of both the capability of the system and the crimp process.

PROBLEM STATEMENT

A large biopharmaceutical company performed a risk assessment to identify risks associated to

crimp defects. The risk assessment tool used was the Failure Mode and Effect Analysis (FMEA). Rating scales for severity, occurrence and detection were classified according to Table 1.

Table 1
Risk Rating Criteria

Rating	Severity	Occurrence	Detection
9	Severe	Frequent	Uncertain
7	Major	Likely	Remote
5	Moderate	Occasional	Moderate
3	Minor	Unlikely	High
1	Insignificant	Remote	Certain

The Severity, Occurrence and Detection ratings are multiplied to calculate the Risk Priority Number (RPN). The RPN is used to weight risks and establish priorities to implement mitigation actions. The company decided to follow Table 2 to assign priorities based on the RPN.

Table 2
Priority Rating

Priority	RPN Value
Low	1 - 74
Medium	75 - 149
High	150 - 399
Critical	300 or greater

The result of the capping process FMEA resulted in 77 risks associated to crimp defects. Most risks are low priority and will not require further actions. Nevertheless, 31 risks identified were medium, high or critical; refer to Figure 4. According to company procedures, any risk medium or higher requires action for its mitigation.

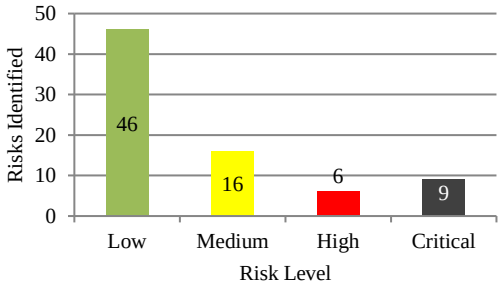

Figure 4
Capping Process Risk Evaluation

Due to the severity of crimp defects, even risks with low Occurrence scores require a low detection score to end up with a low RPN. For this reason, the company decided to increase its detection capability for crimp defects. The goal after the implementation of the mitigation actions is not to have any risk medium or above.

METHODOLOGY

The methodology used for the implementation of the project consisted on 3 phases. In Phase 1, the requirements of the system were established based on the FMEA findings. Phase 2 consisted in the identification of a system capable of complying with the underlying requirements to mitigate the risks identified in the FMEA, and the detail design of the proposed system. The testing and implementation of the system were performed in Phase 3.

RESULTS AND DISCUSSION

The first step in the implementation of an automated crimp inspection system is to clearly establish the requirements. The system requirements specifications purpose is to list the user requirements for the vision system to be installed. A User Requirement is a condition that must be satisfied in order for a system to meet its intended purpose from the perspectives of all stakeholders. User Requirements Specifications focus on what is required without being prescriptive as to how the requirements are met.

Any inspection system to be implemented for the inspection of crimp defects in the company must comply with the requirements of a GMP manufacturing environment. In addition, the company established as basic requirements that the system must be independent from the existing equipment and must fit the existing layout.

Performance requirements are critical to evaluate the effectiveness of the system. In this application, the system was required to perform inspection to 3cc, 5cc and 20cc vial sizes, all of them with a 13mm finish (the area where the cap is placed). Line speeds varies according to vial size

from 460 VPM for 3cc, 260 VPM for 5cc and 100 VPM for 20cc. In terms of performance, the company established that the system must system must operate with 2% or less of false rejects and must have a capability to detect defects with at least 95% of reliability.

Finally, a detailed description of the crimp quality and the defects expected to be detected by the system is required. A good crimp is a complete crimp around the perimeter of the seal in which the aluminum is against the glass in the crimp area. These are the definitions of the crimp defects:

- **Missing Crimp**
  Complete crimp around the perimeter of the seal.
- **Loose Crimp**
  The aluminum seal has not been properly tightened around entire perimeter of the vial lip.
- **Partial Crimp**
  Complete crimp in only part of the perimeter of the seal
- **Rippled Seal**
  The aluminum seal that surrounds the stoppered vial lip has a rippled or wavy appearance underneath.
- **Nose**
  The seal shows a bump on the crimp area.
- **Missing Flip-Off Cap**
  The plastic flip-off is absent or removed from the cap of the sealed vial.
- **Missing Cap**
  The aluminum cap is absent or removed from the vial.
- **Missing Stopper**
  The aluminum cap is crimped but the stopper is missing from the vial.

Out of the eight defects related to the crimp process, six of them can be detected by inspecting the object from any side because the defect impacts the 360° of the crimping. Having the ability to detect defects from one view significantly simplifies the design. At this point, a decision was made to pursue with the smart camera vision system the detection of the six defects detectable with a single camera. The two defects that do not impact the 360° of the crimping are Partial Crimp and Nose. Failure modes associated with Partial Crimps were reviewed and because they are minor defects with a low severity score, these risks are low and no mitigation actions are required. For the nose defect, a detection mechanism was identified and will be discussed later.

The selection of the smart camera was made based on the established requirements and the capability of the systems available. Smart cameras are typically used in applications where the decision is made on absence/presence conditions, as in the case of missing cap, missing flip-off and missing stopper. They are also frequently used for applications where the pass/fail criterion is based on measurements falling within a range. Figure 5 shows a conceptual representation of an inspection leading to a discrete decision, either pass or fail. The inspection criterion for the parts in Figure 5 makes it easy to make a decision, the cap is either present or not, and about any vision system will perform such an inspection with ease.

Figure 5
Inspection Discrete Decision

The biggest challenge in implementing a vision system to detect crimp defects is in inspecting and making a decision for crimp quality based on attributes that cannot be measured. The attribute under inspection does not lead to a discrete decision, but rather a gradient of possibilities that need to be evaluated and weighted to reach a conclusion. Similarly, when tolerances between good and bad parts overlap due to components variability, the pass/fail decision must be made with more than just a measurement. The difference in cap height between a good crimp and a loose crimp will fall within the components acceptable specifications.

Figure 6 is a conceptual representation of the relation between an actual crimp, and its quality, defect classification and risk severity. A pass/fail decision cannot be established by a single attribute or measurement. Due to components variability, a good crimp might have an overall cap height greater than a missing crimp.

In this sense, the vision system must mimic the human thinking process in its ability to inspect a part and make a pass/fail decision based on unique scenarios, weighting different types of conditions observed in each part.

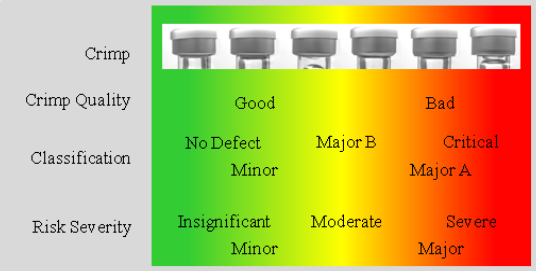

Figure 6
Crimp Quality Gradient

An effective vision system design must be able to evaluate several characteristics of each inspected part, and make a pass/fail decision based on the overall conditions observed for those attributes that do not follow an absent/present pattern or that cannot be compared to a specific measurement.

The selection of the crimp inspection system was based on the system capability to differentiate the features of the different types of crimping.

Several smart camera systems were evaluated for the crimp inspection process. All evaluated systems complied with the minimum requirements in terms of functionality and availability of inspection tools. Cognex developed Geometric Pattern Matching Technologies, marketed under the brand name PatMax® and PatQuick®. These technologies "learn" an object's geometry using a set of boundary curves and then look for similar shapes in the image without relying on specific gray levels. The result is an improvement in the ability to accurately identify objects despite changes in angle, size, and shading. This type of technology fits the need of the crimp inspection in the sense that rather than measuring a specific attribute, it compares the features of the inspected parts against a standard and provides a score to be used in conjunction with other tools to make a pass or fail decision.

Biological products cost per unit is very high. Having line speeds varying from 100 to 460 Vials per Minute and vials sizes ranging from 3cc to 20cc, one minute of production can be equivalent to about $1,000 worth of product. If there is a persistent condition in the equipment rendering vial defects, the sooner the defects are detected; the least amount of product is wasted.

The ideal location for a crimp inspection system is the capping machine. Most new capping machines are designed with integrated inspection vision systems. The capping machine in this case was not designed to integrate a vision system. Due to space limitations, especially when producing 3cc vials, it is not feasible to adapt a smart camera inside the machine. The next best location is the trayloaders infeed conveyor. At this location, there is enough space to install the required hardware to perform the crimp inspection and the means to prevent defects to continue the flow. Another advantage of this location is that the same personnel loading the trayloaders with trays can handle the inspection system; therefore, additional headcount is not required for its operation.

The principle of operation for the design of the crimp inspection vision system consists of performing 100% inline inspection of vials coming from the capping machine as they pass by the trayloaders infeed conveyors. Good vials are allowed to continue to the trayloading operation. If a vial fails the automatic inspection criteria, two bladders, one before the camera and another after the camera, inflates, stopping the flow of vials. The crimp inspection local display will show the vial failing the inspection. All vials trapped between the bladders will be manually inspected. Any defective vial then is manually removed. The system is then manually reset by pressing a pushbutton, which will retract the two bladders allowing the flow of vials again to the trayloader.

The proposed design principle, although not fully automatic, is the less expensive to implement and the one with the least impact on the current equipment and layout. By stopping the flow of vials with bladders instead of installing a reject system, the design is simplified. Taking into consideration that the expected crimp defect rate is low, if the system is capable of maintaining a low false alarm rate, it will have minimum impact in the throughput. Considering that in this vial filling line the constraint in terms of throughput is the vial filling machine, occasional stoppages in the crimp inspection station shall have no impact in the overall throughput of a lot. The vial filling line design consists of two trayloaders because one trayloader alone cannot keep up with the throughput of the vial filling machine. The throughput of the vial filling machine when running 3cc vials is 460 VPM while one trayloader throughput is 375 VPM. At 5cc, the throughput is 260 VPM filler versus 280 VPM the trayloader and at 20cc is 100 VPM filler versus 200 VPM the trayloader. Since there are two trayloaders, at worst the trayloaders capacity is about 60% more than the filler, therefore, there shall be no concern on occasional stops.

The Cognex Inspection System inspects vials on the upper part of the body. Inspection window is the same for all three vial presentation (3cc, 5cc and 20cc) since they all have the same vial finish of 13mm. The system was mounted on a rack and pinion stage system that allows for camera height adjustments. The system main hardware components consist of a Cognex Camera with lens, a backlight, an external trigger, a mounting base with height adjustment, a PLC, a stack light, a flow control mechanism and a control panel for each trayloader. Figure 7 illustrates one of the two inspection stations at the trayloader infeed conveyor.

The overall hardware cost of the system, $34,110, is significantly lower than the cost of PC Based Vision Systems available in the market. One of the reasons the cost is significantly lower is that the designed system utilizes the existing transport system for the vials, which is an advantage of the smart cameras. They can be installed in small places.

Figure 7
Inspection Station

Most vision tools are based on scores in terms of how close a feature of an image is in relation to the defined criteria in the tool. For this reason, the best method to develop a vision system application is by collecting images of "good" parts to teach the system, and challenge it with "bad" parts to confirm the system is able to distinguish between them. In this project, more than 2,000 images were collected of "good" items to tune the tools. In addition, at least 10 pictures of each defect to be inspected were taken for additional tuning. Stored images are played back as many times as needed to test the tools. One important consideration is that since stored images are loaded faster than the camera can take pictures, the total inspection time of stored images is less than the actual time of inspection. Care must be taken not to exceed the available time to inspect parts when the camera is taking the pictures.

Several image setup steps were required to produce a clear image for a process running at 460 parts per minute. The basic image setup configurations include setting the camera exposure time, the backlight pulse time and intensity. The exposure time was set to 8.000 milliseconds (msec). This parameter must be long enough to allow the acquisition of a clear image, but short enough to avoid distorted images and avoid adding too much time so that the inspection cannot be completed on time. In addition, as part of the setup, a calibration was performed to convert pixel count in the image to engineering units, in this case, to inches. Filters were

added to a section of the image to enhance it, as shown in Figure 8.

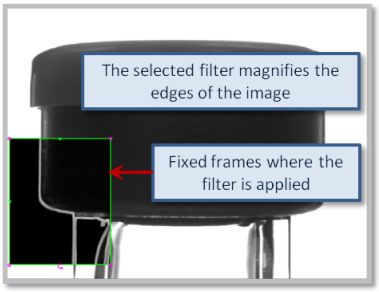

Figure 8
Image Enhanced with Filters

Now that the image is enhanced, location tools were programmed to detect features found on the enhanced filter image. They were programmed to identify the shape of the transition from the side to the bottom of the vial in each side using the PatQuick® tool. Figure 9 shows the tool for the left side, a similar one was developed for the right side, as with all other tools that were develop for both sides of the vial. The Model patter was taken from a good vial.

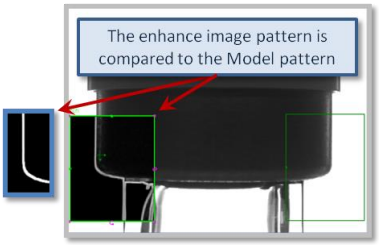

Figure 9
Part Location Tool

If any of the parts location tools returns a score less than 80, the part is considered a defect and a fail signal is triggered, otherwise, it is submitted to additional inspection criteria.

The inspection tools used for this application included Presence / Absence tools, Measurement tools and Math & Logic tools.

The first tool was set to find the top edge of the cap flip-off, refer to Figure 10. If this edge is not found, is an indication of a missing cap or a missing flip-off. In addition, this tool is used with other tools to evaluate the height of the cap to identify potential missing stoppers. The Edge Presence/Absence Tool is used to determine the presence or absence of linear edge features that fall within the specified parameters. The Edge Presence/Absence Tool is one of the faster tools, with the ability to recognize edges features much quicker than a Pattern Presence/Absence Tool.

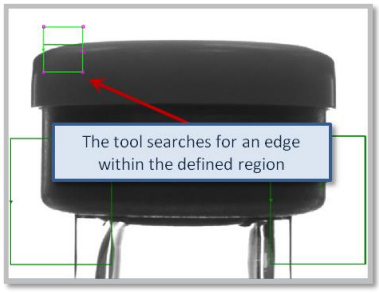

Figure 10
Flip-Off Edge Inspection

The next inspection tool was set to find the edge at the bottom of the crimp area, refer to Figure 11. It is also an Edge Presence/Absence Tool. If the bottom edge is not found, it might be an indication of a missing crimp, or a missing stopper. If this tool fails, the system triggers a fail signal.

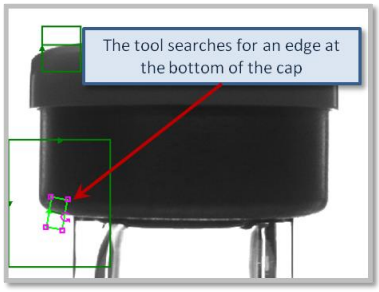

Figure 11
Cap Bottom Edge Tool

The next tool is the first measurement tool used so far. Measurement tools are used to measure distances, diameters, angles and area of features in an image. The Distance tool computes distance between any two input features, and report the calculated distance. The result is in pixels, or in the engineering unit setup in the calibration of the image.

The distance tool was setup to measure the distance between the top of the flip-off and the bottom of the crimp, refer to Figure 12.

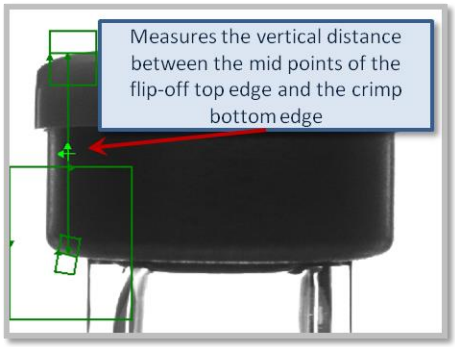

Figure 12
Cap Height Tool

If the measured height of the cap at the left or right side is within 0.29 and 0.33 inches, the part continues the inspection process, otherwise, a fail signal is triggered. This tool captures missing crimps, some loose crimps and some rippled seals.

The next sets of tools are used in combination in order to calculate the width of the cap, refer to Figure 13. First, edge tools are used to find the left and right side of the cap. Then, another tool measures the distance between the mid-point of the left and right edge tools to get the width of the cap.

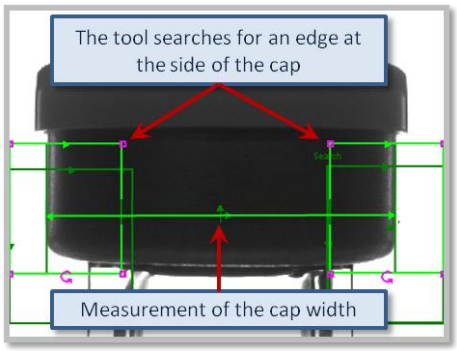

Figure 13
Cap Width Measurement Tool

To avoid false results due to variability in the distance between the cap and the camera, this tool is not used as an inspection criterion. Rather, the proportion between the height and the width of the cap, which is not impacted by small variations in the distance mentioned earlier. The proportion is a mathematical tool entered in the system and is the division between the results from the height distance and the width. The resulting value is compared to a range established in the developmental runs. If the value falls outside the range, the part is considered a failure. This tool detects missing crimps, loose crimps and missing stoppers.

After all the above mentioned tools were set and tested with engineering runs, there were still a number of loose crimps, the most difficult defect to detect, that were passing the inspection criteria. To further refine the inspection, another tool was added.

In this case, a Logic Tools was added to condition the Pass criteria based on the results of both Part Location Tools, refer to Figure 8. The Part Location Tools evaluate the similarity between the inspected pattern and the Model pattern. These tools were set such that the pattern match for both the left side and the right side must be equal to or greater than 80. The next logic tool further refines this criterion by establishing that at least one of the patterns must be equal or greater than 90.

Testing of the system was performed in two phases. The first one was a series of controlled runs in which the system was exposed to 300 trials per crimp defect and 300 trials for good crimps and all testing performed at the high and low speeds. The results from the challenges were evaluated with the Minitab® one proportion test. Results demonstrates that the system is capable of detecting good vials with at least 99.0% reliability and also the system is capable of detecting defects at different speeds with at least 97.6% reliability, which exceeds the requirements criteria in terms of performance established.

Figures 14 to 20 show the results of several inspections in a controlled environment as they are displayed by the system.

Figure 14
Good Crimp

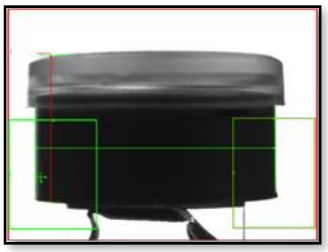

Figure 15
Missing Crimp

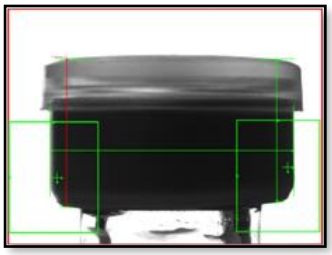

Figure 16
Loose Crimp

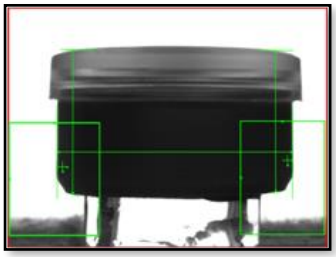

Figure 17
Rippled Seal

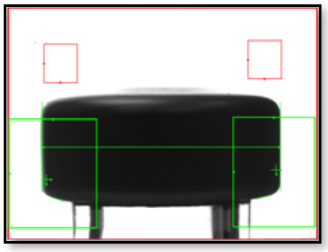

Figure 18
Missing Flip-Off

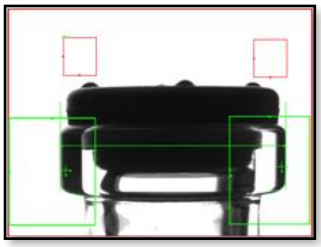

Figure 19
Missing Cap

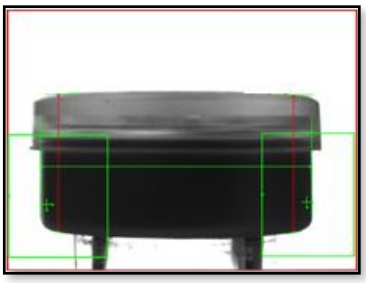

Figure 20
Missing Stopper

The second phase consisted of a normal production run, in which a tightened crimp quality inspection was performed to the units after the trayloader according to company procedures. A sample size of n=315 (per equipment) was used for Critical and Major A Defects. The AQL criteria were 0.016% for critical defects (Acc: 0 / Rej: 1) and 0.43% for Major A defects (Acc: 3 / Rej: 4). The results for the run in trayloader 1 was zero defects in 21,550 units and in trayloader 2 zero defects in 21,905 units.

An evaluation of vials with the nose defects was performed to understand the defects and identify potential root causes. Nose defects are identified by the protrusion of the cap in the crimp area. Figure 21 shows several vials with the nose defect.

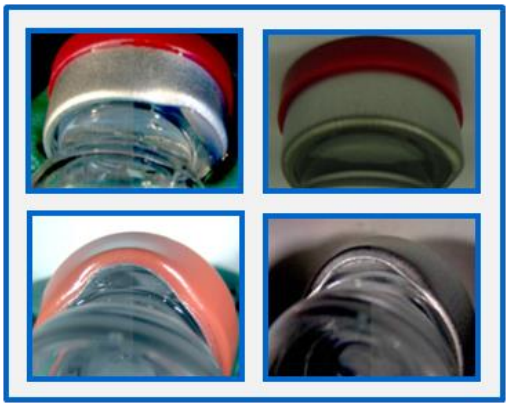

Figure 21
Vials with Nose Defect

The evaluation revealed that if the vial picks off the cap at the incorrect position, the cap might get in contact with the stopper, stretching the stopper as the pressure block applies force to the vial at the crimp station. Figure 22 shows an inadequate cap picks-off and how the cap stretches the stopper.

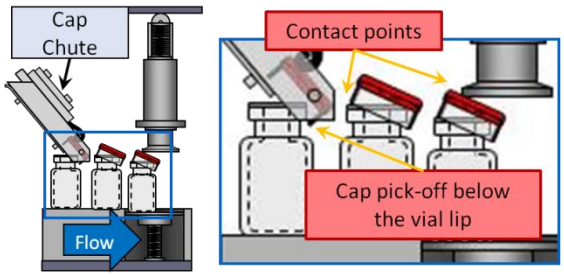

Figure 22
Inadequate Cap Pick-Off

To detect the conditions leading to the nose defect, the cap chute was modified. A thru-beam sensor with fiber optics was adapted to the cap chute to detect when the spring is activated, refer to Figure 23. The output of this sensor was configured in the capping machine such that if it is triggered, the shift register, which indicates the status of vials, is set to indicate a failure.

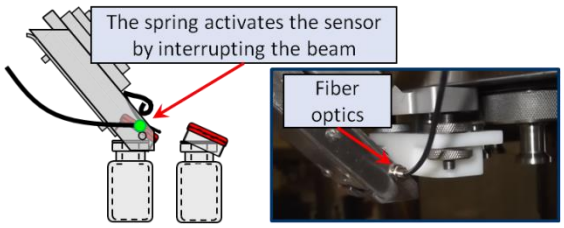

Figure 23
Misplaced Cap Sensor

One advantage of detecting the activation of the spring is that this function does not varies with the size of the vial. The hardware used to detect the activation of the cap chute spring was a Keyence Digital Fiber Optic Sensors and SUNX Fiber Optic Cables. The total hardware cost of this implementation was less than $300.

The sensor was tested in a controlled environment with gauges to ensure it will be triggered if the smallest vial have a misplaced cap, and it will not be triggered if the tallest vial with the tallest stopper was properly capped. Each scenario was tested with 300 trials and the sensor performed as expected in all of them.

CONCLUSIONS

The driver of this project was the result of a FMEA performed on the capping process. The result showed 77 risks, with 31 of them medium or higher. Most risks were reduced by the effective implementation of an in-line 100% Crimp Inspection Vision System. For those defects not detected by the Crimp Inspection Vision System, a Cap Placement Sensor was adapted to the capping machine. Those two implementations reduced all risks scores to low. The total implementation cost of the hardware used did not exceeded $35,000. This implementation shows that an understanding of a particular process with the knowledge of the capabilities of available technologies can lead to powerful solutions without the need of big investments.

FUTURE WORK

Pharmaceutical companies sometimes are reluctant to implement applications because they are difficult to validate. One such application is the detection of fill volume. A similar approach followed by the Crimp Inspection Vision System can be applied in this situation. Rather to look for a perfect system, the implementation of a good system might alert operations if abnormal conditions are impacting fill volume, allowing companies to react at the moment, not when the lot is filled. There is no need to claim such a system would be a lot release criteria, but can potentially alert of conditions such as strangled hoses, leaks and other conditions outside the control capabilities of the filling machine, and can be reflected in gross fill volume failures.

REFERENCES

[1] Cooney, P. H., “Guidance for Industry for the Submission Documentation for Sterilization Process Validation in Applications for Human and Veterinary Drug Products”, U.S. Food and Drug Administration (FDA), Retrieved on 08/06/13, www.fda.gov.

[2] Weber, B., “Smarter Cameras: How Today's Sophisticated, Intuitive Software Takes Smart Cameras to the Next Level”, Vision Online, Retrieved on August 29, 2013 from www.visiononline.org.

[3] Belbachir, A. N., “What Is a Smart Camera?”, *Smart Cameras*, Vol. No. 1, 2010, pp 21 - 23.