Deployment of a laser projection solution for stripes plotting based on Six Sigma DMAIC methodology applied to aircraft painting shop

Gustavo Franco Barbosa\textsuperscript{a*}, Jonas de Carvalho\textsuperscript{a} and Carlos Henrique Pereira de Souza\textsuperscript{b}

\textsuperscript{a}Mechanical Engineering, University of Sao Paulo, Sao Carlos, Brazil; \textsuperscript{b}Production, University of Araraquara, Araraquara, Brazil

(Received 5 March 2014; accepted 25 June 2014)

This paper aims to demonstrate the advantages of using DMAIC Six Sigma method to implement a laser projection system for stripes plotting in aircraft painting shop. The main benefits of this solution are to increase the productivity, improve the final quality of the product, reduce the reworks and consumable materials, as well as attend to the requirements of ergonomics, occupational health, and safety. Thus, better results are expected in terms of process efficiency and technological innovation that are competitive market requirements. Also, it can contribute to improving the painting process of the aircraft, striving for excellence in the processes, thereby reducing the costs of manufacturing and providing greater customer satisfaction. A case study is shown to prove the benefits.

Keywords: DMAIC; laser plotting; automation; aircraft; painting

1. Introduction

Due to globalization, companies are facing market pressures to increase productivity, improve quality, and reduce production cycle time, cost, and time of delivery. Faced with this competitive scenario, companies need to take reliable and efficient decisions in advance in order to implement a better process for their manufacturing tasks, which contributes to the achievement of high standards in terms of technical, financial, and strategic issues. For the aircraft industry, the life cycles of products and growth of varieties of products are not critical when compared to the automotive industries. But there is growing pressure to reduce production costs and the need to accelerate the design and implementation of automatic assembly systems (Barbosa, 2012).

With the increasing application of automation in high performance on aircraft structures, there is a predominant demand of using cost-effective and efficient manufacturing methods to fabricate primary structural components (Salek & Trudeau, 2013). Therefore, some devices accurately project a laser template onto molds and parts to guide operators through the process of part fabrication whether it is ply layup, paint masking, harness assembly, or component location (Virtek, 2014). Herein, a laser projection is used for painting tasks.

In this paper, the application of Six Sigma DMAIC Cycle is used to support the implementation of the automated solution for aircraft painting stripes plotting. The
whole process, measurements, analyses, improvements, and control of all parameters related to development are discussed and demonstrated.

Also, it aims to provide the reader with all the steps involved in the DMAIC cycle to give a robust solution for manufacturing.

Finally, a case study is presented to validate the methodology used in this specific application to support the laser implementation and its beneficial advantages when compared with the previous (manual) process.

2. Literature review

2.1. Automation on production

Future productions call for manufacturing agility to efficiently respond to changes in demand, technologies, and product variation (Jefferson et al., 2013). Faced with this trend, automated systems have been implemented day by day in manufacturing environments.

Increasing use of automation could help aircraft manufacturers compete against future aircraft builders. Also, robots limit the need for human painters, but this kind of work is so unpleasant and repetitive that most workers don’t mind.

2.2. New trends of aircraft painting

Application of robots in spray painting tasks results in low-cost production and persistent quality, and it protects humans from a hostile working environment. Automated planning of applicator’s trajectory requires a model of paint deposition onto the treated surface and formulation of an appropriate criterion for the painting quality (Potkonjak, Đorđević, Kostić, & Rašić, 2000).

Figure 1 shows an example of robots application used for F-35 aircraft painting developed by Lockheed Martin. The system was named RCFS (Robotic Component Finishing System).

Another important application is inside a building in Boeing’s Everett wide-body jet assembly plant. Two robotic machines glide along tracks on either side of a 106-foot 777 wing laid flat. These machines can wash, apply solvent to remove dirt, rinse, and then spray two different paint types. They reach even complex spaces inside the open

Figure 1. RCFS.
Source: Seegmiller, Bailiff, and Franks (2009).
wing root that must be painted for corrosion protection (The Seattle Times, 2013). Figure 2 illustrates this new application of automated painting.

Besides the benefit of speed, the robots ensure pinpoint accuracy on every product and the ability to do multiple tasks simultaneously means a higher quality paint job.

2.3. **DMAIC Six Sigma methodology**

DMAIC methodology is a powerful tool for process improvement.

When these five elements are implemented correctly in a given project, it assures success (Six Sigma Green Belt, 2014).

According to (Glen Barton, 2014), DMAIC methodology process overview needs to:

1. **Measure**: The goal for the measure phase is to focus on the improvement effort by gathering information about the current situation. This will help to narrow the range of potential causes needed to investigate the opportunity in the next Analyze phase. An important part of the Measure phase is to establish a baseline capability level for the performance of the process.

2. **Analyze**: Once data in the baseline performance have been stratified, then one can pinpoint where the problems originate very clearly. This helps to focus on the problem statement. In this phase, therefore, one is able to identify root causes and confirm them with data.

3. **Define**: That’s the first phase. The objective is to define the project’s purpose and scope and collect background information on the process and customer. In this phase, project goals will be agreed based on your knowledge of your company’s strategic business goals, customer needs, and the process that needs to be improved to get you to a higher sigma level. During the Define phase, a Team Charter will be developed with an overview of the process to be improved and information on what is critical to quality for customers.

4. **Improve**: In this phase, one should now be ready to develop, try out, and implement solutions that address root causes. The goal is to demonstrate, with data, that the solutions solve the problem and lead to improvement, and also to make plans for full-scale implementation.
(5) Control: Putting a solution in place can temporarily fix a problem, but the control phase is designed to help make sure the problem stays fixed and that the new methods can be improved over time. The goal of this phase is to evaluate the solutions and plan, maintain the gains by standardizing processes, and anticipate next steps.

These are the key factors involved in DMAIC methodology in Six Sigma green belt process. Figure 3 shows the DMAIC cycle as explained in the bullet list described above:

The DMAIC (define, measure, analyze, improve, and control) process consists of wide range of improvement tools that will surely help to change the mindset of the people in the company. Without a proper methodology and support by great tools, process improvement will be a dilemma in an organization. On the other hand, it will be so fun and interesting.

The following steps shown in Figure 4 explain each phase in DMAIC methodology and how does it act in a Six Sigma process. It shows the DMAIC steps and its related tasks and potential tools that can be used or not, during the analyses for process improvement purpose.

This method guides us in finding the root cause of a specific problem that occurs often. Figure 4 refers to some quantitative and qualitative tools used for DMAIC application. That does not mean that, in a specific situation, other tools could be used.

3. Proposed DMAIC’s specific application

Some sources of problem solving to this specific situation were researched and examined. In this case, evidence suggests DMAIC Six Sigma application because this method facilitates to find a solution that is not known and there is a lack of clarity about how the problem should be approached.

The DMAIC method is rather a general method. Its original task domain was variation reduction, especially in manufacturing processes. This original task domain can be traced to the terminology of early breakdowns of DMAIC into detailed steps (Harry & Schroeder, 2006).

This type of Six Sigma projects coerces problem solving into the framework of statistical modeling of cause-and-effect relations. Problem definition boils down to defining

![DMAIC process overview](image-url)

Figure 3. DMAIC process overview.
Source: Glen Barton (2014).
the right CTQs (control to quality) and problem analysis amounts to discovering the causal influence factors (the Xs), driven by techniques for statistical modeling of cause-and-effect relations. Improvement actions and remedies are derived from established causal relations between these CTQs and Xs, and follow the standard patterns based on statistical model building, such as response surface optimization, robust design, and tolerance design (De Koning & De Mast, 2006).

For ill-structured problems, in which the nature of the problem is not clear, a fact-finding stage aims to establish the real or most urgent problem on the basis of data. This fact finding takes place in the Measure stage in DMAIC. It can be quite elaborate, and typically involves techniques and tools that result in a definitive problem definition (De Mast & Lokkerbol, 2012).

It is recommended to follow all steps of the method to get the root cause of the problem.

### 3.1. Motivation and novelty of this paper

As the technical literature does not provide large volume of information regarding problems of this nature, the DMAIC Six Sigma method is suited as the basis for support and guidance for resolution of the problem. This proposed paper contributes to providing the aircraft painting shop with a better condition to perform their manufacturing works regarding the stripes plotting. A motivating factor for this paper was the incipient and unprecedented information on this subject and also the benefits that can be reached when using an automated solution in a manufacturing environment. The novelty of this work is the application of the DMAIC Six Sigma as a methodology of support for implementation of a laser automated system for stripes plotting on aircraft painting tasks. This integration contributes to assisting the production team (operators, inspectors,
and manufacturing engineers) on painting booth, for achieving the best conditions for the procedures related to speed, quality, simplicity, efficiency, and ergonomics.

3.2. Application to the painting booth

To characterize the problems found in the aircraft painting booth, a well-structured project is described in workpackages to approach it. Routine problems fall in this category and they clarify how the problems can be approached.

Therefore, the DMAIC application to the painting booth is performed to make all analyses and improve the current process. Figure 5 shows the flowchart for DMAIC application, considering the existing process. At Improve step of the flow, it is expected to implement an automated solution for stripes plotting.

All DMAIC method steps are described below:

3.2.1. Workpackage – define

Plotting is done by hands through the masking of 1:1 scale stripes’ drawing (3D files) on templates named ‘templates.’ That is one of the most complex tasks of the painting process, and it corresponds to about 15% of the aircraft painting’s cycle, besides not being a robust process, so prone to failure (errors of interpretation of the drawing). In this conventional situation of manual operation, no precision, no standardization, and a high cycle time for positioning and painting the airplane are required. The manual process is characterized by using templates in 1:1 scale to plot the stripes to be painted on the aircraft.

Figure 5. DMAIC flowchart.
The customer needs according to CTQ’s are as follows:

- Reduction in painting cycles;
- Few people involved in this task;
- Aircraft in accordance with 3D model;
- Assurance of design tolerances;
- Robustness in plotting process;
- Repeatability and standardization;
- Symmetry between the sides of aircraft; and
- Cost reduction with material of templates.

Therefore, this project aims to establish a new process of aircraft stripes plotting, aiming to improve quality, increase the productivity, and reduce the related costs. Table 1 shows the lead time of each step of the project, regarding the implementation on production.

The project’s schedule defines 12 months.

3.2.2. Workpackage – measure

The conventional process comprises the next routines:

(a) 3D design models of the stripes plotting (painting scheme) is made according to customers’ requirement, using CATIA V5;
(b) 3D design model is downloaded, planned, and printed on a 1:1 scale;
(c) The printing is masked on plane by tapes considering the quotas of drawing, i.e. the distances defined in drawings. Usually this information is not in agreement with the design due to the differences and tolerances of manufacturing. At the first product’s plotting, the reference is always the templates and the design (drawing) is updated from the quotas extracted from the printing;
(d) The marks of plotting are made by a pencil along the aircraft. After that, masking is done using paper to provide condition for the painting. After the painting tasks, the masks are removed and reused on another aircraft.

Figure 6 shows an aircraft’s region masked for painting process after marking of stripes is performed by hands.

Figure 7 illustrates the nominal dimensions defined by design and its related tolerances of positioning (+/−10.0 mm) in Table 2.

After the stripes plotting, measurements were made and data collected for 04 (four) aircrafts. Graphic 1 and Table 3 show the dimensions’ values obtained:

According to the values obtained during the measurements on four aircrafts, it is known that many points are out of the tolerances when stripes plotting is done by a conventional process.

| Steps    | Lead time |
|----------|-----------|
| Define   | 1 week    |
| Measure  | 2 weeks   |
| Analyze  | 1 week    |
| Improve  | 5 weeks   |
| Control  | 3 weeks   |

Table 1. Schedule of the project.
Figure 6. Conventional stripes plotting.

![Figure 6.](image)

Figure 7. Nominal dimensions of the stripes plotting.

![Figure 7.](image)

Table 2. Design dimensions.

| Dimension (mm) | Pt 1 | Pt 2 | Pt 3 | Pt 4 |
|----------------|------|------|------|------|
| Minimum        | 165  | 280  | 340  | 405  |
| Nominal        | 175  | 290  | 350  | 415  |
| Maximum        | 185  | 300  | 360  | 425  |

![Table 2.](image)

Graphic 1. Measurement’s values.

![Graphic 1.](image)
3.2.3. Workpackage – analyze

According to (Magnusson, Kroslid & Bergman, 2003), the pragmatic approach of Six Sigma means that if the use of improvement tools enables the identification of which of the input variables to a process affect the output, then it is relatively easy to come up with an improvement solution.

For this project, a cause–effect analysis was used to drive the common causes of the problem.

Based on (Ishikawa, 1976), 6Ms Ishikawa diagram is a product design and a quality defect prevention to identify potential factors causing an overall effect. Each cause or reason for imperfection is a source of variation. Causes are usually grouped into major categories to identify these sources of variation. The categories typically include:

1. **Manpower**: Anyone involved with the process;
2. **Method**: How the process is performed and the specific requirements for doing it, such as policies, procedures, rules, regulations, and laws;
3. **Machine**: Any equipment, computers, tools, etc. required to accomplish the job;
4. **Material**: Raw materials, parts, pens, paper, etc. used to produce the final product;
5. **Measurement**: Data generated from the process that are used to evaluate its quality;
6. **Environment**: The conditions, such as location, time, temperature, and culture in which the process operates.

Figure 8 presents the cause–effect analysis regarding the manual process of stripes plotting.

The key variables are underlined in red color and explained below:

**Method**

Marking on aircraft: this process is basically made by hands, which uses only the drawing quotas as reference and it never matches the real condition. In this case, the operator makes a visual inspection to ensure the continuity and the best shape of stripe in order to reach an ideal situation. Due to an inconstant method, errors usually occur.

Planning of drawing: if the planning process is not done well, it could cause errors in the stripes’ positioning on aircraft. This procedure requires the correct use of specific commands on CAD software, for example use of incorrect scales (1:1), different measurement units (between drawing and software), etc. So, the success depends on the skill of the CAD software user.

Positioning of templates: it is another manual process that requires three people to make the positioning and marking of stripes. In the case of the templates not being aligned, having folds, or even to be out of position, it will give problems in stripes’ positioning.
Manpower

Operator error: as this process is completely manual, it greatly depends on people, i.e. conditions of work, experience, training, and potential failure during the marking process.

Designer error: the current process has no mechanism or Poka-Yoke system to ensure that the stripes’ designs are corrected according to 3D models. It is due to the fact that planning process on the plotter machine and the positioning of them on aircraft do not assure the optimal condition. For these reasons, it is always during the first aircraft’s stripes plotting that the design is adjusted according to the real condition acquired through the plotting of templates. It is not the design that really determines the coordinates of drawings, but the first positioning of template on the aircraft.

3.2.4. Workpackage – improve

This phase is about the generation, selection, and implementation of the solution to solve the problem. According to the Define, Measure, and Analyze phases performed so far, the Improve phase is about being creative and to find a best way to do things better, faster, and cheaper (Pyzdek, 2003).

Based on automated solutions knowledge and author’s experience on manufacturing processes, an idea that could address the root cause of the problem and help to achieve the goal was formulated. The intention is to apply a workable potential solution already available in the market. By this way, laser projectors will be used in this project.

When positioning and laying out large materials during the production, many companies still work with templates or measures manually. Both are enormously tedious and susceptible to mistakes. The laser projectors replace the time-consuming process by projecting even complex contours with millimeter precision. The manual alignment with the clumsy templates and wearisome measuring are now a thing of the past. Furthermore, the laser projection optimizes the work processes and improves the quality thanks to the immediate visual inspection (Lübke, 2013).

Figure 9 illustrates the concept of laser projection system that can be used for several applications. The digital laser projector device uses laser beams to project CAD data directly on the product.

For this kind of application, CAD drawing is displayed on the aircraft with a specific painting scheme. This system is significantly faster than using templates for
marking and manual masking. The laser indicates the steps and shows the position of the stripes and its lines. Also, this solution can be used for drilling holes, cable ducts, pipes, composites, etc.

Figure 10 shows a specific application of laser projection for aircraft painting scheme. It is possible to see the phases of preparation before the final result on airplane.

This system especially accelerates and simplifies the complicated painting tasks preparation of airplanes inside the booth and improves precision.

3.2.4.1. Case study. As a form of proof and certification of the efficiency of the method proposed in this paper, a case study is presented in this topic. It reports the use of a laser automated system for stripes plotting for a NB (narrow body) aircraft in painting booth. The tasks involved the projection of the stripes on fuselage according to the painting scheme, as illustrated in Figure 11:

All tasks had been accomplished by one operator and accompanied by a manufacturing engineer and a quality inspector. Thus, the laser projection using an automated system was performed again on four aircrafts and the results were presented in Graphic 2 and Table 4 as follows.

A comparison between the two methods presented above can show the improvements and advantages when a laser device is used for projection of stripes on aircraft painting. So, the use of laser solution can contribute to fitting the measurements within the tolerances defined by design, due to the precision and repeatability acquired with an automated process.

Also, an important gain related to MH (man-hour) could be obtained with the laser solution application. Graphic 3 shows the total MH (man-hour) required for stripes plotting in both the cases (conventional and laser).

It represents a gain in productivity of 9.5 h per aircraft plotted. In order to make valid and to certify the gain obtained with the laser application, the MH was valued according to the tax ($) related to the manpower’s cost per hour. Table 5 shows the values and its related savings according to the reduction in MH when laser solution is used.

Figure 9. Laser projection.
Source: Lübke (2013).
It is important to emphasize that these measurable savings add to the competitive advantages for the business when laser projectors are used for stripes plotting. NOTE: an investment of $125,000.00 should be spent for laser equipment purchase.

For this case (demand of 10 aircrafts/month), the payback of the investment was returned in about 2.2 years. NOTE: costs associated with programming and maintenance were not considered herein, because they are non-recurring expenses. Thus, the proposed automated solution could contribute to the company’s competitiveness when applied to the painting environment.

Also, some intangible gains (not measured) could be listed below:

- Ergonomic and health conditions due to avoiding undesirable posture of people on aircraft;
- Contribution to the environment by eliminating the needs of paper printing;
Flexibility and standardization faced in the changes of aircraft programs;
DMAIC methodology applied to a specific aircraft situation;
Easiness of transferring data from computer to aircraft;
Know-how for new programs and other applications; and
Innovation and competitiveness.

Table 4. Values of measurements obtained on aircrafts.

|          | Pt 1 | Pt 2 | Pt 3 | Pt 4 |
|----------|------|------|------|------|
| Aircraft 1 | 166  | 285  | 342  | 407  |
| Aircraft 2 | 170  | 281  | 343  | 422  |
| Aircraft 3 | 184  | 289  | 358  | 417  |
| Aircraft 4 | 183  | 295  | 352  | 410  |

Graphic 2. Laser device – measurement values.

Graphic 3. MH for stripes plotting.
3.2.5. Workpackage – control

The final phase of DMAIC cycle is the control phase. According to (Pyzdek, 2003), this phase makes sure that the improvements made last longer. It is often done by modifications of compensation and incentive systems, policies, procedures, budgets, and other management systems. Once the solution has been implemented, the process should be monitored to secure that the desired improvement target has been achieved (Magnusson et al., 2003).

To make sure that permanent improvement takes place for this project, the following actions were done:

- Elaboration of a laser plotting process script in order to create a well-explained procedure for the operators;
- Implementation of TPM (total productive maintenance) to avoid stops of the laser projectors;
- Planning of training for more people (production, maintenance, and process) to prepare for the future;
- Improvement actions to take care of problems that may occur during the tasks in the booth;
- Creation of SPC (statistical process control) to measure and analyze the process condition;
- Development of plans to prevent future problems that can arise; and
- Updated documentation that can be available at any time for use by anyone.

4. Conclusion

The results presented in this paper assure that the application of the proposed automated solution supported by DMAIC Six Sigma methodology contributes to innovation on production environment in order to make the company more competitive according to the challenges faced in the market.

Discussing the results of this paper, it is important to emphasize the practical and relevant contribution of laser plotting system based on DMAIC used on shop floor, making the aircraft’s painting process easier. This customized method also cooperates significantly to increasing productivity, quality, and flexibility due to providing updated data on real time, reducing wastes and consumable materials, paperless concept deployment, minimizing errors during stripes plotting, and ergonomics issues.

Evidence demonstrated in the case study certifies that the application of the DMAIC method in laser plotting application for aircraft’s painting contributes significantly to adding value in terms of technology and strategic matters. It increases the level of the company’s competitiveness. Furthermore, it could be said that the level of information obtained right away on the shop floor provides a quick response to the production needs when this kind of laser solution is used. It is important to say that the DMAIC method establishes the integration between the automated solution and manufacturing environments.

| Δ of MH | Tax (manpower) in US$ | # aircraft/month | Annual saving  |
|---------|-----------------------|-----------------|---------------|
| 9.5     | 50                    | 10              | $57,000.00    |
Finally, it can be concluded that the proposed customized methodology presented in this paper meets the most important needs required by the aerospace competitive market. It guides the painting’s support team for sustaining a manufacturing system with focus on gains in productivity, flexibility, and innovation. This solution can also be applied to aircraft maintenance tasks.

References
Barbosa, G. F. (2012). Development of an analytical model for implementing automation in aerospace manufacturing, driven by requirements of DFX – Design for excellence and lean manufacturing methodologies (Doctoral thesis). University of Sao Paulo – EESC, Sao Carlos, Brazil.
De Koning, H., & De Mast, J. (2006). A rational reconstruction of Six Sigma’s Breakthrough Cookbook. International Journal of Quality and Reliability Management, 23, 766–787.
De Mast, J., & Lokkerbol, J. (2012). An analysis of the Six Sigma DMAIC method from the perspective of problem solving. International Journal of Production Economics, 139, 604–614.
Glen Barton, G. (2014). DMAIC process overview. ICP – Innovation Consultancy Partnership. Retrieved January 23, 2014, from http://icpartnership.com/sixsigma.html
Harry, M., & Schroeder, R. (2006). Six Sigma: The Breakthrough Management Strategy Revolutionizing the World’s Top Corporations. New York, NY: Crown Business.
Ishikawa, K. (1976). Guide to Quality Control. Tokyo: Asian Productivity Organization. ISBN 92-833-1036-5.
Jefferson, T. G., et al. (2013). Review of Reconfi gurable Assembly Systems Technologies for Cost Effective Wing Structure Assembly. Montreal, Canada: SAE Aerotech International Publications.
Lübke, T. (2013). Technical article laser projection: Relief when laying out large, flat materials. Lüneburg: LAP GmbH Laser Applikationen.
Magnusson, K., Kroslid, D., & Bergman, B. (2003). Six Sigma the pragmatic approach (2nd ed.). Lund: Studentlitteratur. ISBN: 91-44-02803-2.
Potkonjak, V., Đorđević, G. S., Kostić, D., & Rašić, M. (2000). Dynamics of anthropomorphic painting robot – Quality analysis and cost reduction. Robotics and Autonomous Systems, 32, 17–38.
Pyzdek, T. (2003). The six sigma handbook. New York, NY: Mc Graw Hill. ISBN: 0-07-141015-5.
Salek, H., & Trudeau, P. (2013). Development of low cost fuselage frames by resin transfer molding. Montreal: SAE Aerotech International Publications.
The Seattle Times. (2013). Boeing using robots to boost 777 output. Business/Technology. Retrieved May 29, 2013, from http://seattletimes.com/html/businesstechnology/2021082952_boeing777xml.html
Seegmiller, N. A., Bailiff, J. A., & Franks, R. K. (2009). Precision robotic coating application and thickness control optimization for F-35 final finishes. Seattle: SAE Aerotech International Publications.
Six Sigma Eine Produktgruppe. (2014). Six Sigma roadmap: DMAIC. Wiener Neustadt: Merten International und FH Wiener Neustadt.
Six Sigma Green Belt. (2014). DMAIC methodology. Retrieved January 21, 2014, from http://six-sigma-green-belt.com/?p=127
Virtek. (2014). Three-dimensional laser templating system. Connecticut, CT: Connecticut, CT: Gerber Technology Company.
Wilhelm, S. (2013). Boeing automating 777 wing painting. Puget Sound Business Journal.