

Parts Quality Management: Direct Part Marking of Data Matrix Symbol for Mission Assurance

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Abstract— A United States Government Accountability Office (GAO) review of twelve NASA programs found widespread parts quality problems contributing to significant cost overruns, schedule delays, and reduced system reliability. Direct part marking with Data Matrix symbols could significantly improve the quality of inventory control and parts lifecycle management. This paper examines the feasibility of using direct part marking technologies for use in future NASA programs. A structural analysis is based on marked material type, operational environment (e.g., ground, suborbital, Low Earth Orbit), durability of marks, ease of operation, reliability, and affordability. A cost-benefits analysis considers marking technology (label printing, data plates, and direct part marking) and marking types (two-dimensional machine-readable, human-readable). Previous NASA parts marking efforts and historical cost data are accounted for, including in-house vs. outsourced marking. Some marking methods are still under development. While this paper focuses on NASA programs, results may be applicable to a variety of industrial environments.

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1. INTRODUCTION

Manual data entry and data collection became problematic during the early stages of part identification largely due to human error. Technological advancements in the 1960s and 1970s allowed for the achievement of better product coding that improved the accuracy and speed of data processing. One of the earliest forms of product coding is barcode technology. Barcodes simplified inventory tracking and management and greatly improved checkout speeds in retail, wholesale, and grocery industries. Realizing the efficiency

that barcodes brought to commercial applications, the United States Department of Defense (DoD) mandated barcodes for all DOD material in 1981 [1].

However, traditional barcode technology (i.e., one-dimensional barcodes) had several limitations. For example, more than one barcode could not be read at a time [1]. Barcodes had short-range readability, and many did not possess automated tracking [2]. Traditional barcodes also presented both poor data security and limited storage capacity for characters. In some situations, restrictions related to printing on paper or plastic impeded the application of barcodes on labels [3]. Since traditional barcodes were typically printed on labels, this limited the use of barcodes to certain applications and environments.

Two-dimensional (2D) barcode symbologies can store large amounts of information in a small space. They differ from the one-dimensional (1D) barcodes in that data can be stored in both the horizontal and vertical dimensions. Thus, 2D barcodes are capable of storing over 100 times more data than typical 1D barcodes [4]. Examples of 2D barcode symbologies include the QR code, EZ code, and Data Matrix code. The Data Matrix symbol is the most popular of the 2D barcode symbols. The symbol has been adopted by the automotive, electronics, pharmaceutical, and aviation industries.

Direct part marking (DPM) is an ideal method for applying 2D barcodes to aerospace parts. DPM creates permanency of marks and ensures traceability of a part throughout its entire lifecycle. DPM techniques are preferable when the product is separated from its external packaging and traceability is required. They are also preferable when a part is too small to be marked with barcode labels or tags. Parts that are subjected to environmental conditions that hamper the durability of add-on identification markings are also good candidates for DPM. Furthermore, DPM is the suggested method when part identification is required beyond the expended life of the part [5].

The biggest challenge in a DPM application is to consistently produce good quality markings for parts requiring machine-readable information [6]. Another challenge is ensuring the act of marking does not inhibit the functionality of the actual part. Incorrect or improper application of part marking techniques can lead to damaging a part beyond the level of acceptability. Hence, this paper

will address several concerns of DPM. It will analyze the flexibility, efficiency, marking quality, and limitations of different DPM techniques. The primary objective of this research is to evaluate the pros and cons of different DPM processes and determine the feasibility of implementing specific DPM procedures into future programs for the National Aeronautics and Space Administration (NASA).

2. DATA MATRIX SYMBOL

The Government Accountability Office (GAO) assessed parts quality problems for 21 DoD and NASA programs [7]. Twelve of the reviewed programs were NASA systems. According to the GAO report, the Aerospace Corporation conducted a study and found that “both prime contractors and the government space market lost traceability into parts as suppliers moved from having to meet military specifications and standards to an environment where the prime contractor would ensure that the process used by the supplier would yield a quality part” [7]. Parts quality problems contributed to significant cost overruns, schedule delays, and reduced system reliability. These findings indicate an immediate need for a system that can enhance operability/supportability and reduce life cycle costs.

The Data Matrix ECC 200 symbol is a two-dimensional, machine-readable symbol that can mitigate these problems by enhancing traceability of thousands of parts commonly involved within a single supply chain. The 2D barcode can also be applied to non-paper substrates. An optimal way to ensure that part markings survive the harsh conditions of space is through DPM techniques.

The Data Matrix symbol is a 2D array of square or round cells arranged in contiguous rows and columns that can store information, identify individual components of a larger item, or track items between a sender and recipient [8]-[9]. The standard Data Matrix ECC 200 symbol is highly recommended because of its high accuracy in situations where the code might even be partially damaged or suffers from poor resolution. It is a highly secure marking, and thus, may not be easily counterfeited. The Data Matrix symbol is also used by industries across the world. As a result, it is compatible with nearly all extant part marking techniques [10].

Today, it is common for manufacturers to use human readable designations on parts that have the substrate space for part marking. Yet, there are some parts that lack substrate space for marking; instead they rely on marked packaging for identification. However, once the part is removed from the packaging, the traceability of the part is lost. This results in scrapping parts since there is no verifiable link to a database for tracking the part [8]. Direct part marking of Data Matrix symbols eliminates this problem, as it provides tracking of parts that have insufficient substrate space. This is one of the chief advantages of the Data Matrix symbol: the symbol can be

generated and placed on micro-size spaces while maintaining readability even at low contrast ratios. For example, Data Matrix readers can decode a 50-character code that is only two or three millimeters wide. Etched Data Matrix codes might be as small as 300 micrometers [9]. Direct part marking is the optimal marking method for providing the fidelity needed to apply micro-size, high-density, machine-readable marks such as the Data Matrix symbol.

3. CRITERIA FOR MARKING

Current DPM technologies were selected using [5]. The handbook consists of collective industry knowledge on automatic and data capture systems and provides guidance on how to best apply the Data Matrix symbol to aerospace parts based on prior testing. Assessment of prior testing can be used to determine the survival of part marking techniques in various environments. The International Standards Organization and the International Electrotechnical Commission Standard 15415 (ISO/IEC-15415) is used to measure marking quality by a grading system. Marking is deemed unacceptable when the grade is lower than a ‘C’ during or after service, repair, or overhaul [11]. Ref. [8] gives an extensive overview on the effect of the part environment on various marking processes. The Materials International Space Station Experiment (MISSE) shared results on the marking tests used to certify part identification marking processes for use in Low Earth Orbit (LEO) [11]. The information provided by [8] and the MISSE marking tests will be assessed to determine the durability of marks created from different processes.

4. STRUCTURAL ANALYSIS OF NON-INTRUSIVE MARKING METHODS

Direct part marking can be applied in one of two ways: through non-intrusive marking or through intrusive markings. Nonintrusive markings, also known as additive markings, are produced as part of the manufacturing process or by adding a layer of media to the surface of a part using methods that have no adverse effect on the part. Intrusive markings alter the surface of a part (e.g., abrade, cut, burn, vaporize, etc.) and are considered controlled defects [5]. Poor application of markings can result in degradation of material beyond the point of acceptability. Determining which technique is suitable for a given application is dependent on the part’s function.

Non-intrusive marking methods are recommended for safety-critical parts (i.e., parts which could fail, resulting in hazardous conditions). If intrusive markings are to be used in safety-critical areas, then they must be documented and approved [8]. Examples of non-intrusive markings include automated adhesive dispensing; cast, forge, and mold; ink jet; laser bonding; laser engineered net shaping (LENS);

liquid metal jet; silk screen; and stencil. Ref. [5] provides an overview of each of these techniques. In **Table 1**, some non-intrusive part marking techniques are listed along with their

description, common applications, advantages and disadvantages.

Table 1. Non-intrusive direct part marking methods.

| MARKING PROCESS | DESCRIPTION | ADVANTAGES AND DISADVANTAGES |
|--------------------------------------|---|---|
| Automated Adhesive Dispensing | Deposits precise amount of adhesive on a repeatable basis Applications: Electronics | Advantages <ul style="list-style-type: none"> Time/pressure dispensing is a data-driven process, flexible, simple to operate Auger system handles a wide range of adhesives Piston pump systems are not as sensitive to viscosity changes; capable of creating larger dots; consistency at higher speeds Disadvantages <ul style="list-style-type: none"> For time/pressure systems, higher speeds result in less consistent dots For piston pump system, sensitive to air in fluid and complex cleaning procedures For auger systems, sensitive to viscosity changes |
| Cast Metal Marking | For DPM of investment casting parts, wax coupons are directly attached to the wax pattern of the part to be marked before being put through the investment casting process. For sand casting, the Data Matrix symbol would be placed into a recess of the mold pattern before the sand mold is compacted and formed. Applications: End use parts subjected to high stress, Non-machined surfaces | Advantages: <ul style="list-style-type: none"> Less costly than injection molding; relatively little residual stress Disadvantages: <ul style="list-style-type: none"> Sand casting may produce rough surfaces as opposed to die casting Cell profiles with aspect ratios substantially greater than 1 may be difficult to produce using the investment casting process Coupon overall thickness less than 0.02-inch (0.51mm) may be difficult to handle later in manufacturing operations, such as attachment to wax pattern |
| Molding | The hot, viscous fluid is pressed or injected into a die under considerable pressure, where it cools and solidifies. Variants of the process use gas pressure or vacuum to press a heated polymer sheet onto a single-part mold. Applications: Glasses, thermoplastics, Elastomers, Polymer Foams, Rubber | Advantages: <ul style="list-style-type: none"> Elaborate shapes can be molded Blow-molding and thermo-forming are rapid, low-cost molding processes Adapted to materials that are viscous when molten Disadvantages: <ul style="list-style-type: none"> The die must withstand repeated application of pressure, temperature, and the wear involved in separating and removing the part, and therefore it is expensive |
| Forging | Characters raised or depressed depending on method of manufacture, unless otherwise specified by drawing Applications: Non-machined surfaces only | Advantages: <ul style="list-style-type: none"> Can increase the strength of the final product Disadvantages: <ul style="list-style-type: none"> Hot forging of metals allows larger changes of shape but generally gives a poor surface and tolerance because of oxidation and warpage Cold forging gives greater precision and finish, but forging pressures are higher and the deformations are limited by work hardening |

| MARKING PROCESS | DESCRIPTION | ADVANTAGES AND DISADVANTAGES |
|-------------------------------------|--|--|
| Ink Jet | Precisely propels ink drops to the part surface, after which the fluid that makes up the ink dot evaporates, leaving a colored die on the surface of the part creating the pattern of modules that make up the mark. Applications: Post-packaging, Warehousing, Automotive | Advantages: <ul style="list-style-type: none"> • Low entry cost • High speed • Easy to read if contrast is good Disadvantages: <ul style="list-style-type: none"> • Not considered permanent by some industry standards • Dot registration can vary • Higher cost consumables • Mark quality dependent on surface cleanliness • Difficult to read if contrast is poor |
| Laser Bonding | An additive process that involves the bonding of a material to the substrate surface using the heat generated by an Nd:YAG, YVO ₄ , or CO ₂ laser. Applications: Materials with high absorptivity | Advantages: <ul style="list-style-type: none"> • Laser bonding overcomes the two most serious limitations of thermocompression bonding, namely the need for high temperature and high pressure, which are known to cause damage to the device and affect its long-term reliability. Disadvantages: <ul style="list-style-type: none"> • Coatings are application-specific • Generally limited to flat or slightly curved surfaces • Restricted to materials thicker than 0.001-inch (0.025 mm) |
| Laser Engineered Net Shaping | A laser beam focuses onto a metal substrate to melt the upper surface. A deposition head then applies metal (powder or fine wire) into the molten puddle to increase the material volume. Applications: Fully dense metal parts (i.e., composed of stainless steel, aluminum, copper, titanium, etc.) | Advantages: <ul style="list-style-type: none"> • Residual stress may result which means an increase in strength and ductility of material Disadvantages: <ul style="list-style-type: none"> • Has been found to leave a poor surface finish • A scan speed that is too fast and held at a high temperature can cause large grains to grow • A powder temperature that is too cold can lead to inadequate fusion, and a powder temperature that is too hot can cause plasma to form |

5. STRUCTURAL ANALYSIS OF INTRUSIVE DIRECT PART MARKING

Intrusive DPM methods require less marking area for data matrix identification symbols. Thus, parts with marking areas significantly less than 6.75mm would benefit more from intrusive DPM techniques than from nonintrusive DPM techniques. Laser marking is considered the most appropriate technique for producing the Data Matrix symbol on small parts due to the flexibility of the laser spot size [6]. However, some laser marking machines can be large, and the implementation cost of the method can be high compared to other intrusive part marking methods [12]. As previously mentioned, intrusive part marking methods, especially laser marking, should not be used on safety-critical applications because they can potentially damage a part. If an intrusive method is used for a safety-critical application, careful engineering analysis and metallurgical testing is required before application. The following discussion provides an overview of intrusive DPM techniques such as direct laser marking methods and other commonly used intrusive DPM techniques.

Direct Laser Marking Methods

The use of lasers to mark parts is becoming particularly popular for the application of Data Matrix symbols. Laser marking provides the following capabilities: high speed, consistency, and precision [13]; highly readable and permanent marks; marks applied at angles on complex surfaces; adjustable sizing of marks to fit the available space [14]. However, laser marking thermally alters the surface of the substrate. Therefore, the engineer should consider several factors before deciding to employ laser marking. For brittle materials, the process can lead to the propagation of cracks emanating from the regions hit by the laser. For very thin metals, the process could cause deformation such as curling or wrinkling effects [15]. The laser irradiated material may oxidize or burn off, melt and resolidify, evaporate, ablate, undergo chemical change or changes to its microstructure and physical properties [16]. Understanding these and other limitations can assist in deciding the best marking method for the part. Some of the latest techniques in laser marking include Laser Induced Surface Improvement (LISI™), Laser Induced Vapor Deposition (LIVD), Gas Assisted Laser Etch (GALE), laser etching, laser coloring, laser engraving, and laser shot peening.

Laser Induced Surface Improvement—LISI™ laser marking uses a laser beam to melt a pre-placed powder mix of alloying compounds into the surface of the base metal, precisely and according to the desired pattern [16]. It is meant to form an improved alloy with high corrosion resistance and wear properties. The coating, which is a formulated powder, protects the marking from corrosion and wear. However, this method modifies the chemical composition, microstructure and properties of the base metal surface [16]. It has the potential to create undesirable defects such as pores or unwanted compounds, like brittle intermetallics [16]. A reduction of fatigue resistance has also been observed when using a pulsed laser for LISI™ laser marking [16]. A continuous wave laser may be preferable over a pulsed laser to limit the reduction of fatigue resistance.

Project MISSE tested different part marking techniques such as LISI that would expose both human-readable marking and machine-readable marking to LEO environments (i.e., vacuum, solar UV radiation, micrometeoroids and space debris, atomic oxygen, and deep thermal cycles) [11]. Project MISSE assessed the marking quality of using the LISI process after a year exposure to Low Earth Orbit. The marking process received ‘passing’ preflight and post-flight verification grades as defined by ISO/IEC-15415 [11]. LISI™ laser marking has generally been used on metal parts that rust when exposed to their normal operating environment. It may not be a suitable process for glass materials, but it may be modified to work well with some ceramics and plastics. More empirical information on employing the process in these material applications is needed.

Laser Induced Vapor Deposition—LIVD is a coat and marking method developed by Siemens. The heat coming from the visible spectrum laser vaporizes material from a marking media trapped under a transparent part. The generated heat causes a buildup of gaseous vapors and droplets. These vapors and droplets condense onto the cooler transparent surface to form a hard, uniform coating that is applied in a prescribed pattern. The process does not require the use of high heat or seal gas/vacuum chambers. The machine-readable markings can be formulated to be read using optical readers and sensing devices like X-ray, thermal imaging, ultrasound, magneto-optic, radar, capacitance, or other means of sensing [5].

The marking tests conducted by Project MISSE used glass as a base material, and the materials that were marked using the LIVD process were brass and tin. The Data Matrix symbol markings using LIVD all received passing grades as defined by the ISO/IEC-15415. When the marking material was tin, the marking process received an A for its preflight and post-flight verification grades. When the material was brass, the process received a B for preflight and post-flight verification grades. This is clearly indicative that the marking quality can vary for different materials. It is recommended that markings applied to glass substrates

using the LIVD process should be applied to the interior (unexposed) side of the item [11]. LIVD is limited to transparent materials only. The process is also limited to lasers operating in the visible spectrum.

Gas Assisted Laser Etch—Laser marking conducted in an ambient environment often results in a limited degree of contrast between the engraved mark and the substrate background. This can limit marking speed and the number of different materials that could be marked. One technique that could enhance contrast and increase readability in a gaseous environment is Gas Assisted Laser Etch (GALE). This marking method is minimally intrusive because it is performed under low power settings. An assist gas reacts with the material under the influence of the laser energy to produce a reactant that is a different reflective color from the background. The assist gases might be reducing, oxidizing, or inert depending upon the target material. A high contrast, readable mark is created at the coincident point of the laser [8].

The University of Tennessee Space Institute evaluated LISI and GALE marks for aerospace marking applications and determined that the marking processes are durable for application in harsh environments [17]. Project MISSE assigned an overall pre-flight verification and post-flight verification grade of ‘A’ for GALE markings exposed to LEO environments after 4 years (2001-2005). The factors evaluated included the percentage of contrast, axial uniformity, print growth, and error correction. GALE markings are limited to only metallic alloys. Since the technique involves laser etching, it may create debris and affect the surface of the substrate.

Laser Etching—Laser etching involves heating the substrate surface to a level that causes substrate surface melting. Laser etching has been used in the past for enhancing the labeling of automotive parts [18]. It gained popularity in the automobile industry due to its ultra-high speed, which is essential to shortening manufacturing and delivery turnaround time for an ordered car. Laser etching is frequently used to mark plastics that contain pigmented materials that are discolored by the laser beam in order to produce a striking color contrast. Additives can be applied to plastics that do not mark well to enhance contrast [5]. Laser etch is generally limited to 0.001 inch maximum depth and performed at lower power settings. When using laser etch on safety critical parts, it is best to coat the part before marking it. Aluminum parts marked using laser etching had high passing preflight and post-flight verification grades after exposure to LEO environments after a year.

Laser Coloring—Laser coloring involves employing a low power laser to pass slowly across the substrate surface in order to create contrast for the marked area. The process is performed without burning, melting, or vaporizing the substrate material. Though the process involves fewer surface disruptions than other intrusive marking methods, it can have adverse effects on parts that have been previously

heat-treated. It can reduce the corrosion resistant properties of some stainless steel alloys. These effects can be minimized by adjusting laser settings. The process is not recommended for parts thinner than 0.10-inch [5]. Government testing was conducted to assess the effects of chemical environments on the survivability of markings from different part-marking processes during ground and suborbital operations [8]. The chemical environments included deicer, fuels, grease, hydraulic fluid, and lubricating oil. Part markings from laser coloring remained legible when exposed to grease, but testing is not complete for assessing how the markings tolerate other chemical environments.

Laser Engraving—Laser engraving is performed by vaporizing the surface of the substrate material. As the material is vaporized, exhausted ventilation removes any fumes or smoke [19]. Laser engraving is expensive and labor-intensive, but it is the quickest laser marking method that can be produced. Laser engraving markings remain readable in most ground and sub-orbital operations and LEO operations. The marking has a lower contrast than other marking processes, however. Laser engraving is acceptable in safety-critical applications when used in conjunction with the “coat and remove” process. This process involves coating a part with a medium of contrasting color that is removed afterwards by the laser to expose the underlying material. Laser engraving may produce micro cracking on some materials [5]. Hence, engineering approval or the expert advice of a metallurgist is required before using the process in safety critical applications. Marking tests performed by Project MISSE revealed high grades for parts that used glass as a base material and copper as the marking material. Direct laser engraving involves the removal of part material, but laser engraving using the “coat and mark” process does not remove part material.

Laser Shot Peening—Laser shot peening has been used in the past to improve fatigue lifetime of Navy aircraft arrestment hook shanks [20]. The process is similar to the concept used in shot peening in that it induces residual compressive stress into metal surfaces. An intense beam of light is directed onto the part’s critical surface which creates high-pressure plasma that generates a shock wave, driving the compressive stress deep into the surface [21]. The surface to be peened is under a laminar flow of water called the “tamping layer”. The tamping layer acts as an inertial stop when the high-pressure plasma is formed. The plasma is formed in nanoseconds and the mass of the water prevents it from expanding, thus driving the energy into the work piece surface [21].

An ablative layer is applied in the locations that will be laser peened. The ablative layer prevents the surface from slightly burning. The resulting compressive residual stress lowers the mean tensile stress. Cracks are generally suppressed in a compressive surface. Thus, the residual compressive stress typically provides excellent protection against crack initiation and growth as well as fatigue failure. It is

beneficial to induce as much compressive stress with as little cold work as possible. More cold work results in a rougher surface finish along with less desirable compressive surface stress [21]. It has been noted that pulse duration, irradiance, and number of treatment layers have the most significant impact on the residual stress developed by laser peening. An example of such research is the considerable effort that has been applied to studying the modeling residual stress profiles in friction stir-welded 7075-T7351 aluminum alloy specimens [22]-[23] and high strength 300M steel [24].

Laser shot peening marking can be used on any non-brittle material that undergoes plastic strain upon surpassing its stress yield point. It will not work well on materials that fracture such as glass. Laser shot peening can be controlled by varying the pulse intensity, focal spot size and location, and the pulse number at each peening location. One of the major disadvantages of laser shot peening is its relatively slow speed and high cost in terms of the processed surface area. The laser pulse energy has to be sufficiently large and the laser spot size has to be sufficiently small. It is mostly used in applications where shot peening is not applicable [25]. Altogether, laser shot peening is an advantageous part marking method— especially for safety-critical parts that cannot be marked with the current nonintrusive part marking methods. The marking process received a B for preflight and post-flight verification grades. This constitutes an acceptable marking quality, but represents fixed pattern damage up to 9 percent.

Other Intrusive Direct Part Marking Methods

Other common intrusive DPM methods used to produce machine-readable symbols include dot peening, electro-chemical marking, and engraving/milling. Dot peening offers low implementation and operating costs compared to laser markings, but it is more time-consuming and less versatile in respect to material applications. Dot peening is highly durable, but it can alter the surface of a part. In addition, dot peening can produce low contrast marks and difficult readings.

Electro-chemical marking is good for round surfaces and stress-sensitive parts [13], but this type of marking process cannot be applied to nonconductive materials. Electro-chemical etching produces highly durable marks, and there is no debris from the process. However, the process can potentially produce toxic by-products. Electro-chemical coloring is one of the least intrusive marking processes, but it is less durable than electro-chemical etching.

Engraving is great for glass, plastic, phenolic, ferrous, and nonferrous metals. Engraving also offers low implementation and medium operating costs [13]. However, engraving can also be time-consuming. This marking process is not recommended for 2D barcode symbols.

Many of these methods have been used by the aerospace, automotive, medical, and pharmaceutical industries for years. So unlike many of the laser marking methods previously discussed, there has been an extensive amount of testing for these methods in ground, suborbital, and LEO environments. Ref. [8] showed that marks created using dot peening or mechanical engraving remained readable after being exposed to a large number of ground, suborbital, and LEO environments. Government testing on electro-chemical marking processes has not been completed.

6. COST BENEFIT ANALYSIS STUDY

The cost of implementing machine-readable Unique Identification (UID) markings into future NASA programs using DPM techniques will depend on a number of factors. The costs will depend on the marking methods to be used and where the items will be marked (i.e., in-house versus outsourcing). The item's characteristics will also determine the cost of using a particular DPM technique. For example, factors such as part geometries and material properties will influence the cost of marking. Recurring and non-recurring costs must also be considered when determining the lifecycle costs of marking each item.

Understanding these costs is essential to Parts Management. Parts Management promotes costs savings, enhances logistics readiness, reduces maintenance cost, and enhances interoperability [26]. The six specific drivers for which Parts Management can lead to cost benefits are:

- Engineering and design,
- Testing,
- Manufacturing,
- Purchasing,
- Inventory, and
- Logistics support [26]

For DPM, engineering and design of Parts Management would relate to the selection of marking technique, intangible costs, and recurring costs—the last entails replication of effort, part analysis and approval, and maintenance. During the testing phase, it is determined whether or not a marking method would be acceptable for the intended use. The cost benefit here is avoiding the loss of resources associated with improperly applying a DPM technique. During the manufacturing phase, cost benefits are noticed based on cost savings from the lack of need to purchase new equipment or tooling or additional storage at the manufacturing site [26].

Cost benefits are realized if the business decides to use existing equipment and tools for part marking. In addition, any avoidance of purchasing new equipment/tools reduces

procurement-related costs [26]. The cost for storage increases as new equipment/tools for new part marking methodologies are placed in service. For logistics support, introduction of new methods requires changes to information systems, supporting documentation (i.e., maintenance manual, user handbooks, etc.), and modification of existing parts databases. Obsolete methods and equipment may also negatively affect cost benefits.

DoD and Private Industry Cost Benefit Analysis Studies on UID Implementation:

The DoD conducted a cost benefit analysis study of UID implementation into their supply chain [27]. The study compared the costs of in-house part marking with outsourcing part marking. The data for these comparisons can be found in **Table 2** and **Table 3**, respectively. The marking costs for in-house marking are significantly less than outsourcing, but initial setup costs are extremely high. Cost, timeliness, infrastructure, and in-house benefits are some factors the DOD suggests program managers consider when selecting either in-house part marking or outsource part marking.

A study was also conducted by A. T. Kearney on barcoding business benefits [27]. Cost reduction and improved efficiency were found in the following areas: merchandising and sales time handling data, customer service time dealing with purchase orders, finance time reconciling invoices, inventory out of stocks, logistics costs, warehouse and direct store delivery, speed to market, shelf tag and scan errors, and data cleaning. Smaller businesses are expected to have less cost benefits with implementing the 2D Data Matrix as the volume of parts is a function of costs. DoD's cost benefits for marking parts with 2D barcoding are significantly greater than the cost benefits NASA would observe because of its larger volume of parts. Hence, when looking at historical cost benefits for 2D barcode implementation, more focus should be placed on businesses that work with a small to medium range volume of parts in their supply chain. This may help provide NASA with a better estimation on potential cost benefits.

Table 2. In-house part marking costs.

| Marking Approach | Method | In-house Marking costs (very dependent on order quantities) | Minimum Infrastructure to take advantage of UID and AIDC (optional) |
|-----------------------------------|------------------|--|--|
| <i>Life-lasting gummed labels</i> | Polyester | \$2000 printer + \$700 software + \$0.05 per label | Readers: \$500 →\$1000 per reading device |
| | Metal Foil | \$2000 printer + \$700 software + \$0.05 per label | Readers: \$500→\$1000 per reading device |
| <i>Data Plates</i> | Plastic | \$5000 machine + \$0.50 per label (very low volume) | Readers: \$500→\$1000 per reading device |
| | Metal | \$20,000 laser + \$0.50 per plate | Readers: \$500→\$1000 per reading device |
| <i>Direct Part Marking</i> | Inkjet | \$10,000 machine + \$0.50 per mark | All methods (except laser bonding) will require more expensive low-contrast readers costing \$1200→\$2500 per reading device |
| | Chemical Etching | \$2000 printer + \$300 chemetch + \$700 software + \$0.50 per mark | |
| | Dot Peening | \$10,000 machine + \$0.10 per mark | |
| | Laser Bonding | \$15,000 laser + \$0.30 per mark | |
| | Laser Etching | \$25,000 laser + \$0.20 per mark | |

Internal Market Research: Survey of representative sample of marking companies [27]

^aIn-house marking costs are based upon non-complex part geometries and conditions for the part to be marked.

Table 3. Outsourcing part marking costs.

| Marking Approach | Method | Outsourced Marking Costs ^a | Minimum Infrastructure to take advantage of UID and AIDC (optional) |
|-----------------------------------|------------------|---------------------------------------|--|
| <i>Life-lasting gummed labels</i> | Polyester | \$0.10→\$0.50 per label | Readers: \$500→\$1000 Per reading device |
| | Metal Foil | \$0.20→\$1.00 per label | Readers: \$500→\$1000 Per reading device |
| <i>Data Plates</i> | Plastic | \$0.50→\$2.00 per plate | Readers: \$500→\$1000 Per reading device |
| | Metal | \$0.50→\$3.00 per plate | Readers: \$500→\$1000 Per reading device |
| <i>Direct Part Marking</i> | Inkjet | \$1.00 per mark | All methods (except laser bonding) will require more expensive low-contrast readers costing \$1200→\$2500 per reading device |
| | Chemical Etching | \$2.00 per mark | |
| | Dot Peening | \$3.00 per mark | |
| | Laser Bonding | \$2.00 per mark | |
| | Laser Etching | \$2.00 per mark | |

Internal Market Research: Survey of representative sample of marking companies [27]

^aOutsourced marking costs are based upon non-complex part geometries and conditions for the part to be marked.

Another strategy in gathering cost benefit estimates for UID implementation may be to look at implementation in past NASA programs. However, because UID implementation has not been thoroughly executed in the past at NASA, there is not much historical data to reference for estimating UID implementation costs through DPM techniques. Change requests (CRs) on UID marking through DPM techniques — such as CRs typically sent to contractors such as Boeing from previous missions— may be referenced to gain an idea of the estimated cost of incorporating the Data Matrix symbol onto aerospace parts aboard NASA programs.

Nevertheless, implementing the Data Matrix symbol is more beneficial to Mission Assurance and Quality Control. It increases supportability and safety of systems and equipment. It mitigates the risk of human error. UID provides information on what particular part was used in which implementation [26]. UID provides the history of a part, which can reveal its manufacturing, stresses over its lifecycle, and any possible faults. The UID can reveal the location of the part, for instance, if it is currently on a mission, disposed of or on the shelf. The bottom line is that the improved management of parts, reliability, safety, and improved efficiency of implementing the UID can be as much of a deciding factor as any cost benefits.

Implementation of UID for the International Space Station

The International Space Station (ISS) currently uses a labeling system known as the Inventory Management System (IMS) [28]. This is an automated tracking and identification system that incorporates human readable information and machine-readable information on to parts. The barcode is in conformance with Code 39 barcode symbology [28]. The IMS may be used to complement the manufacturer or vendor label – which supplies the manufacturer’s identification, part number, batch-serial number and/or stock number per MIL-STD-130. The primary purpose of the IMS is to provide information on the location, status, maintenance, and resupply information for parts. In accordance with [28], items that are too small to be labeled with IMS, such as screws and other consumables, must be placed in a bag. However, once these items are separated from their packaging, it becomes difficult to trace their lineage. This could result in parts becoming unapproved and eventually scrapped from service. The other limitation of the IMS database system is that it requires manual data updates or line-of-sight barcode scans, one item at a time [29]. This can make the parts verification process very time-consuming.

Another parts management issue that may become problematic in the future is NASA’s use of a conservative approach for determining, obtaining, and delivering spare parts to ISS [30]. The expected lifetimes of the replacement units are determined by a combination of the performance of the systems and the manufacturers’ predictions. Thus far, this has proven to be a sufficient approach. However,

according to the Government Accountability Office (GAO), NASA found failure rates of diverse replacement units lower than the manufacturers’ predictions [30]. If this continues, NASA may find itself purchasing an excess of spare parts. The GAO also conducted an assessment of several large-scale projects at NASA: finding that parts obsolescence and purchase of spares contributed to the increased costs of the Orbiting Carbon Observatory 2 [31].

The DoD, in particular, has experienced problems with unapproved parts and an excess of spare parts in its inventories. In an effort to achieve what is known as total asset visibility (TAV), the DoD required materials meeting certain requirements to be marked using item unique identification (IUID). The DoD selected the ECC 200 Data Matrix symbol as the technology used to mark IUID on parts. An IUID supplies parts with a globally unique identifier and “enhances operational readiness and efficiency by greatly reducing the time required for acquisition, repair, and deployment of items” [10]. It reduces lifecycle costs by reducing the amount of time it takes to conduct an inventory. It improves speed and accuracy of data processing and data transfer [32]. This reduction in labor time and errors would also result in reduced lifecycle costs. A similar unique identification policy implemented at NASA could help provide the same benefits as it does for the DoD. To reduce the excess of spare parts in the future, and thereby wasteful spending, UID can improve repair times and part reliability by tracking the maintenance cycle of critical parts.

7. CONCLUSION

Applying the Data Matrix symbol using direct part marking techniques helps ensure traceability of parts throughout their lifecycle. Direct part marking techniques that involve laser marking processes may be the optimum techniques for applying the Data Matrix symbol to very small items where space is limited. It enables more data to be stored on very little substrate space. Safety-critical parts should always be marked using a non-intrusive method unless documented and approved for intrusive part markings. When selecting the best method for a given part, program managers should consider the durability, structural compatibility, affordability, and manufacturing constraints associated with applying the technique. Researchers are continuing tests on the International Space Station to assess marking quality of different techniques on parts manufactured from different materials and operating in Low Earth Orbit conditions. More empirical research is also being conducted to assess the quality of readability for parts after exposure to ground and suborbital environments and service, repair, and overhaul environments.

The cost of implementing Unique Identification for aerospace parts in future NASA programs (and possible current programs like the International Space Station) is dependent on variables such as part geometry, part material,

marking technique, part function, environment, and method of manufacture (e.g., in-house or outsourcing). A review of the cost and time savings from past implementation of Item Unique Identification by the DOD showed the potential for similar benefits to NASA. An analysis of current data acquisition and part verification problems experienced on the International Space Station suggests that the implementation of Unique Identification can improve speed and accuracy of data processing and data transfer. The future of unique identification marking such as the Data Matrix barcode promises advanced reporting of part failure for targeted repair, improved preparation for maintenance, and conservation of resources.

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BIOGRAPHIES



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