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Article

DESIGN TO ACHIEVE ACCURACY IN INK-JET CYLINDRICAL PRINTING MACHINES

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Abstract: Machines for direct digital inkjet printing on cylindrical containers are a new technology out on the market. Their commercialization in the industrial sector has been affected by their high precision. This leads to the use of mechanisms with narrow manufacturing tolerances and to the search for topologies that have the least accumulated error without affecting quality. Machines with topologies to work on flat substrates have printing and productivity problems working on cylindrical substrates. This research paper presents the qualitative design of a direct digital inkjet printer working over cylindrical substrates comparing five mechanical topologies; three topologies with radial distribution and two topologies with parallel distribution. The aim of these topologies is to find the precision, quality and efficiency of the printer taking into account the restrictions present in its construction. Each topology has separate constitutive mechanisms, it is analyzed the tolerance ranges between the print head and the substrate whose cumulative error maximizes the inkjet print resolution to determine precision. From five Topologies, number 1,2 and 5 meet the requirements. the topology 2 meets the requirements but it is not able to be developed due to current technological limitations.

Keywords: Inkjet; Printer; Topology; Tolerance;Machine

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1. Introduction

Graphic arts printing is looking at penetrating in a new market niche. For this reason, direct-to-object is an emerging technology which is achieving a performance that makes it a very competitive player in cost and versatility [1]The advantages of this technology are supported in the non-use of ink transfer media and the versatility to change, but the quality and efficiency are still for small runs only [2]. The graphic information on the surface of the cylindrical containers is very important for the product image besides indicating the content, it is the publicity and the identity of the company that manufactures it. The food, chemical, pharmaceutical, beverage, cosmetics and cleaning supplies industries use cylindrical containers for much of their production, and, impact on the environment is key in this type of technology and would negate the real needs in product advertising [3], [4]. Since its inception, inkjet printing has been developed with the premise that the surface on which it acts is flat, but recently, the direct impression is being developed on cylindrical containers and other solid ones with different forms and materials [5], [6]. This is a task with a lot of challenges since inkjet printing for flat surfaces still does not match the speed and, in some cases, it doesn't match the quality of the flexographic printing, either. For this reason, it is necessary to look for new topologies that assure the quality and productivity. In [5], Thorp makes a first approximation to the challenges that are in development for a prototype for printing on non-flat surfaces. It is argued that one of the greatest challenges in the development of the prototype is the location of the

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printheads against the solids, since this angle has a great influence on the alignment and, therefore, on the print quality [7].The worldwide printer manufacturing industry consists of two segments of manufacturers: those that build all the constituent elements which are focused on large markets, and those that construct small batches or custom equipment using parts from specialized subsystem factories (Original Equipment Manufacturing OEM) [8], [9][10]. The printing machines and their applications are developed according to the speed of the development of the technology that is given in the printheads [11], [12]. The challenge of the innovation of these machines is being developed by small manufacturers. In [11], Cahill makes a detailed review of the main printheads available on the market for commercial printing machine manufacturers, which will be the starting point for mechanism constraints. When the printheads are not subject to the same structure or the substrate moves to each print head, it leads to an error position that is proportional to the print accuracy. The industrial printing machines have high accelerations but are light then the dynamic load is not high. Which simplifies the structure in addition and favoring low error that may arise in the different configurations of the printers. A printhead which is between 96 and 384 nozzles per inch has a range between 38 and 250 microns and this is the maximum separation of the print between printheads which presses the manufacturing of the machine to the level of high mechanical precision[13]. During the machines period of operation, the relative starting position of each container is called the index [14]. The indexing in machines where the topology requires the container to be released and then transported to the next printhead is monitored so that the different colors Cian, Magenta, Yellow and Black, with their English acronym (CMYK), are not superimposed. The fact that there is displacement of the container when a color is printed is one weakness of the topologies compared to a planar substrate.

The first machines to print on non-flat surfaces preserved the topology of flat machines. The result is effective if the travel distance of the drop is short, otherwise problems may occur when wide 2D flat printheads on 3D surfaces present distortions due to the differential area [13], [15] .In figure 1, it can be seen how the impression of points spaced at equal distances, ΔX does not have an equivalence on the cylinder surface where this distance becomes a variable ΔS, deforming the original. From this it is concluded that when the flat topology is used, the container must have the axis of rotation parallel to the longitudinal axis of the head; otherwise, taking into account that industrial printheads can reach up to 70 mm in length, the nozzles at the ends are very high above the container.[5]

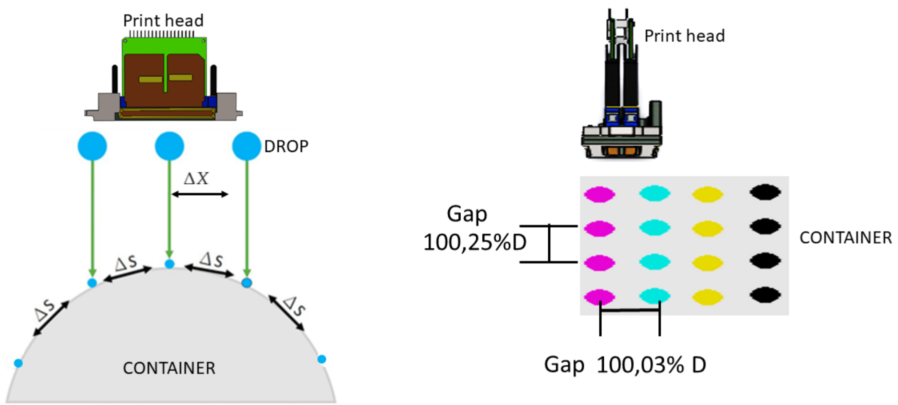

Figure 1. 2D-3D Distortion and Drop Gap

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Cylindrical containers are made of different materials; polyethylene, polyester, polystyrene, PVC, acetate, glass, it's the most used for home and chemical industrial, paper, paperboard, synthetic paper is the most used for offices and recycle process. This diversification of the substrates to be printed requires that the factors involved in the process, such as surface tension, spreading and others, which affect print quality [16], be studied in the ink. In this article, is developed, the methodical design that analyzes, through a black box, the flow of energy, matter and information, and all the subsystems needed to design a machine are detected by the method of the transparent box. In section 3, five possible topologies are presented, analyzing their configuration and their constitutive mechanisms. Section 4 compiles the technological parameters that condition the design to print on cylindrical containers. Section 5 presents the analysis, the evaluation of the topologies and the conclusions.

2. Methodology

As a first step in the design, it is analyzed if the existing machine can be adapted for the new product [17], designs prototypes of printers for non-flat surfaces have been developed starting with Cartesian structures of two axes (sheet forward, transverse movement print head) for flat substrates [18] .In this topology, the paper feeder is replaced with the cylindrical container. Utilizing these same axis points for the paper feeder allows the rotation of the cylindrical container during the printing of non-flat surfaces. The printer approaches the desired result with the print head, but when using an industrial print head and a cylindrical container, the figure deforms due to the increase in the trajectory distance of the drop from the nozzle to the substrate (varies for all nozzles) then we start to construct Cartesian structures of four axes in which the print head is positioned in height and aligned with the axis of the container. The table is moved longitudinally and the fourth axis which is mounted on the table contributes to the rotation of the container.

The technique used is the Methodical Design [19] which is founded on the work of Pahl and Beitz [20]. The first step was a black box which described the input and output of energy flow, matter, and information of the whole system. In this case, as shown in Figure 2, print is the main function.

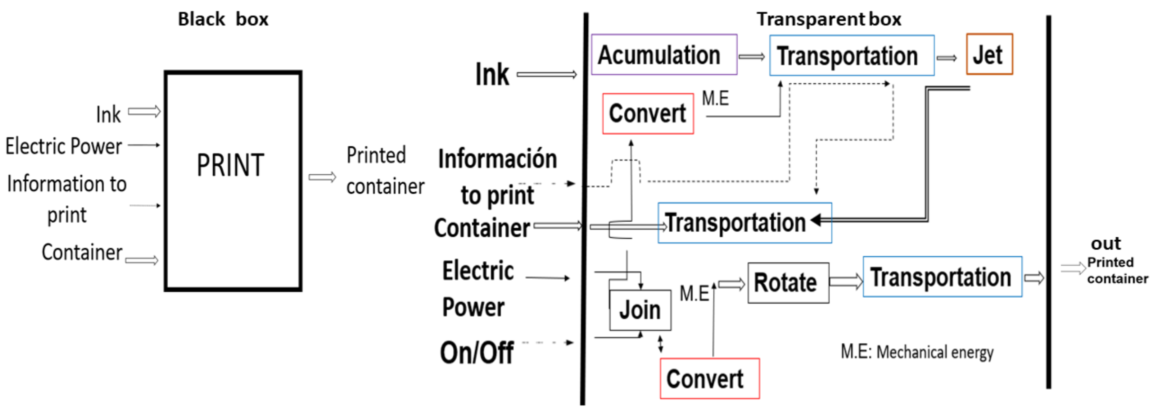

Figure 2. Transparent and black Box

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In the next step, the subsystems were identified. Each subsystem fulfills a function and finds the relation between them in a graphic called a transparent box. One box, with its respective functional verb, is assigned to each sub-function. As seen in Figures 2, these boxes are connected according to the flow. For example, the information goes to a driver that controls the ejection of ink onto the container.

Then, for each subsystem, several mechanisms, modules or devices are searched that fulfill the respective function. These are called the function or sub-system carriers by means of a functional structure.

Combining or permutation solutions of the main function are constructed using the carriers. Each solution is called a topology because it only includes functions that have a direct relationship with the location accuracy between the printheads and the container. Depending on the requirements, the commercial characteristics of the transparent box subsystems [20] [21] are chosen. In this case, the transparent box consists of 7 sub-functions: feed - transfer - hold - rotate - eject - dry - eject which affect the container or printheads. The feeding and removal of containers from the printing area does not make a difference in the qualification, hence they are not included. For the analysis of tolerance of the parts composing the subsystems, it is assumed that low mechanical adjustment follows the norms set forth by ISO 286: 1988 or equivalent, ANSI B4.2-1978, EN 20286: 1993, JIS B 0401, DIN ISO 286, BS EN 20286, EN 20286 CSN.

According to tests by Mercier, et al., which use a print head with a 760 nozzle, there is a pronounced decrease in print quality when the erroneous recording exceeds 50 microns [7], [22].The error in the register is given both in longitudinal and transverse displacement as well as in alignment or parallelism between the print head and the container [13]. To find the relative positioning error between each print head and the container (register), the cumulative error of the different mechanisms that compose each topology is evaluated. The tolerance field is used to evaluate the accumulated error of each topology. According to the International Committee for ISO Standardization [23], the tolerance required in precision machine parts is within the grades of IT6 to IT7 for axes, and IT5 to IT6 for holes in a range between 18 to 30 mm in diameter [23], [24], [25].

The following describes the types of errors that appear and influence the registry. Upon evaluating each topology, identifying the maximum error in the registry could affect the quality of the impression.

The first type of error is static and occurs when the mechanisms are left relatively misaligned or moved in the manufacturing or the set-up. To eliminate static errors in precision machines, the ones designed include static adjustment screws that allow the relative displacement of the mechanisms in a small length or angle. Static errors are not considered an accumulated error because they are eliminated as was previously mentioned.

The second type of error is a dynamic error. This happens when a mechanism moves, and by the effect of the tolerance in its construction, it does not reach an exact position. The result is that between the print head and the container there is longitudinal, transverse and misalignment displacement.

As the container moves through the printing process, the occurrence of an error due to the shift of the container or the printheads is called indexing. There are two ways this error can occur. Figure 3, illustrates how a rotation which is more or less than 360 degrees as the container passes from one print head to another may manifest itself. The error is usually attributed to the container shifting or skidding in the holding mechanism as it turns.

When the container has a length greater than the print length of the print head, the print head must print twice with displacement in order to cover the second pass that follows. Errors can occur in this displacement. In figure 3, the displacement of the print head is observed when it surpasses the distance between the drops or it is superimposed in the impression.

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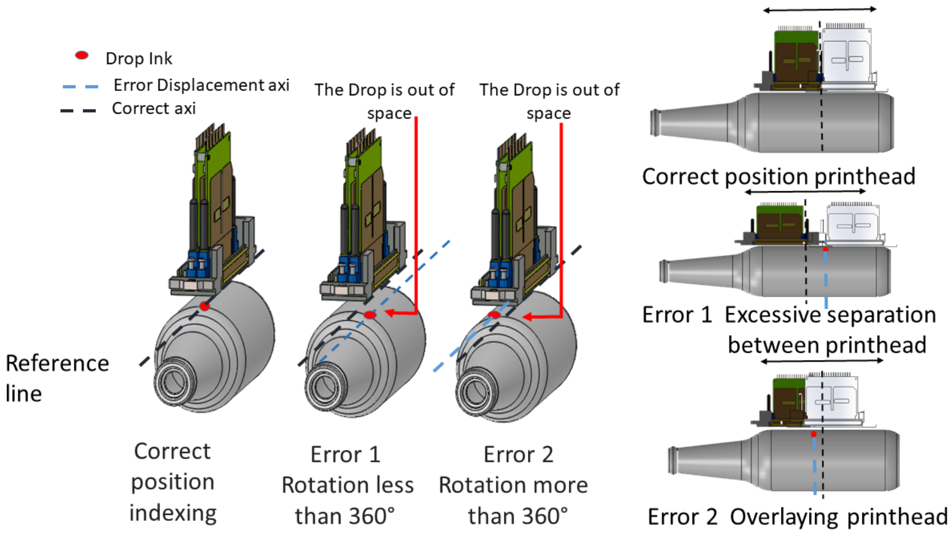

Figure 3. print head Cylinder rotation and Translation error

When a drop comes in contact with the surface, it tends to spread and penetrate the surface or spreading. The diffusion of the drop on the surface can (depending on parameters of ink and substrate) be irregular to maintain the required resolution [16],[26].

Another phenomenon is the drop break up which occurs when the drop is broken during the trajectory from the head to the substrate. The effect on the quality of the substrate is the mixture of colors. The main cause is the increase in the distance between the print head and the substrate. Other influencing factors are the drop velocity and the drop surface tension. [27] [28].

3. Topologies

The models can be classified into: concept machines, demonstration machines and productive equipment.

In concept machines for example [profactor] presents a robot that works on sports shoes. The time it takes is very high then it is only demonstrative. Another robot is presented by Xennia, which takes pieces of form and places them under the heads in positions that are changing. The productivity is low.

In the demonstration machines for example the Advanced digital solution CP100 [29] presents a topology of advance in line and individual impression. Because the concept machine works only with one container and not with multiple container, the performance is low. It could be similar to the topology 2 with the difference that this topology works with several containers at the same time.

For productive machines are registered: Tapemati presents the CPrint mini machine which has an alternative conveyor belt that receives a container that is located under each print head and then ejects it and returns to take another container. The topology is similar to the topology 1 with the difference that this topology works with multiple containers and the band is continuous. The print width is only one pass that correspond the print head width. The production is 800 containers per hour, but the container dimension is limited. Dobuit Machines presents the machine 9150 digital machine with topology and productive characteristics equal to the previous one but doubles the size of the container in diameter from 50 to 100 mm.

3.1. topology 1

In topology 1, Figure 4 all the printheads are mounted in a monostsructure (CMYK) or (CMYK + white background + transparent varnish) [29]. The monostructure moves vertically to fit the diameter

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of the container and shifts depth to cover the entire length of the container. The separation distance between print head is greater than the maximum diameter of the containers. As seen in Figure 4, containers are printed simultaneously. The containers rotate in order to be printed and to advance longitudinally, which is to be located under each print head. In figure 4 the phase diagram shows each movement. The Translator is represented by the blue line, rotation is represented by the red line, the print head is represented by the green line and the movement of the printheads is represented by the purple line. The black arrows indicate when the container is held (up arrow) and released (down arrow). The x-axis is the time and the y-axis is the displacement.

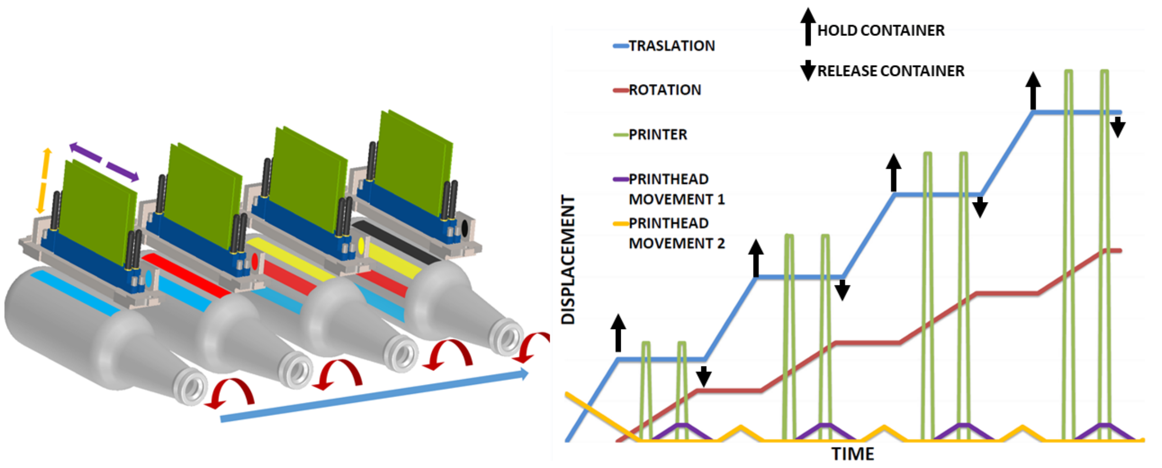

Figure 4. Topology phase diagram topology 1

3.2. *topology 2*

In topology 2, Figure 5 all the printheads are mounted in a linear monostructure (CMYK). The monostructure moves vertically to fit the diameter of the container. Four containers are printed simultaneously. Each spindle has the possibility of adjusting a small distance (10mm) in a longitudinal direction in order to synchronize with the starting index. The containers rotate to be printed, and at the same time move longitudinally in the package as they are printed so that they do not stop.

In topology 2, Figure 5 all the print heads are mounted in a linear monostructure (CMYK). The monostructure moves vertically to fit the diameter of the container. Four containers are printed simultaneously. Each spindle has the possibility of adjusting a small distance (10mm) in a longitudinal direction in order to synchronize with the starting index. In the case when the length of the containers is longer than the print head, the containers rotate to be printed, and at the same time move longitudinally in the package as they are printed so that they do not stop, it is obliging the software and the file management between print heads are different. This type of technology is having not been developed yet. In figure5, it can be seen how the topology works.

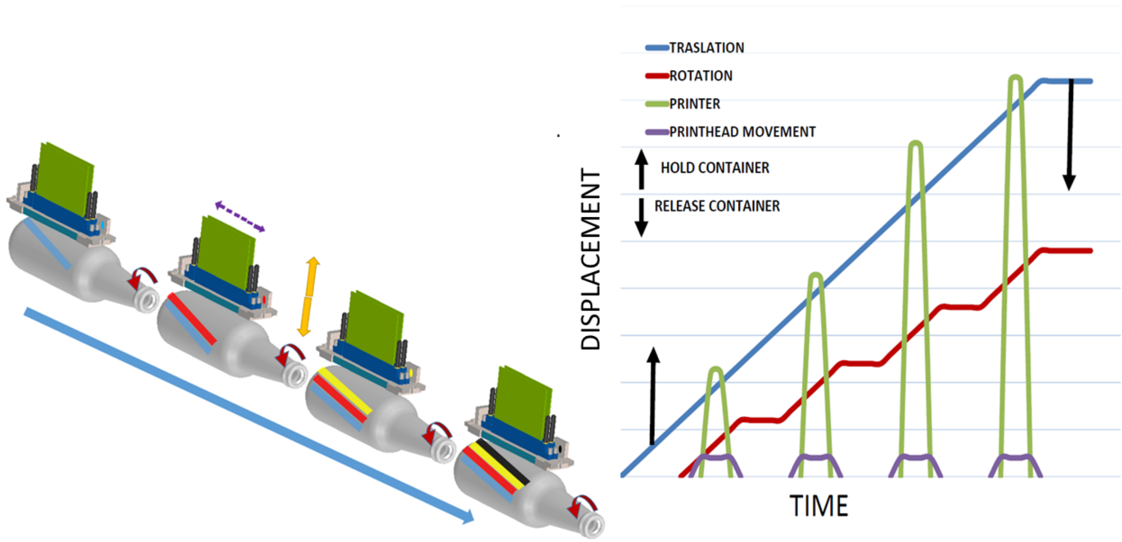

Figure 5. Topology phase diagram topology 2

3.3. topology 3

In topology 3, Figure 6 all the printheads are mounted radially in a mono-structure (CMYK). The height adjustment (diameter) of each print head is independent. The mono-structure is shifted in depth to cover the entire length of the container. This rotates in order to be printed. Although this topology initially presents advantages for the construction of small machines of prototyping, it is temporarily postponed in the analysis by the inclined position of the printheads. At the moment, there is no reference of an application with an inkjet print head in a position that is different from the perpendicular position to a substrate in a flat position.

3.4. topology 4

In topology 4, Figure 6 all the printheads are mounted radially in a mono-structure (CMYK). The height adjustment (diameter) of each print head is independent. The mono-structure is shifted in depth in order to cover the entire length of the container. Four or more containers are printed simultaneously. The containers are mounted on a radial cylindrical turret. The container rotates on its own axis to be printed. Then the turret rotates and the container is then moved to place it below the next print head. The turret at the bottom has two stations that serve to enter and exit the containers. Although this topology initially presents advantages for the construction of machines of high productivity, it is temporarily postponed in the analysis by the inclined position of the printheads. At the moment, there is no reference to an application with an inkjet print head in a position different from the perpendicular position to a substrate in a flat position.

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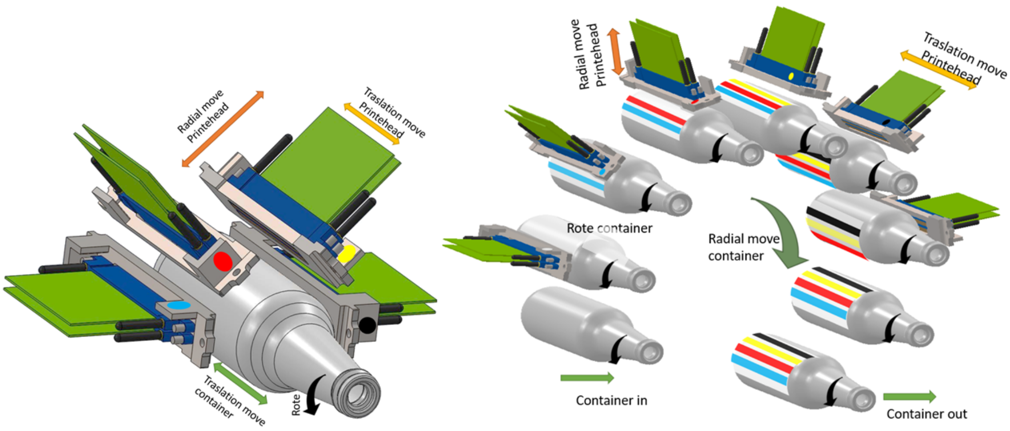

Figure 6. Topology 3 and 4

3.5. *topology 5*

In topology 5, Figure 7 all the printheads are mounted radially in a mono-structure on the same plane (CMYK). The mono-structure moves vertically to fit the diameter of all containers. The printheads move individually in depth (radial) to cover the entire length of the container. Four or more containers are printed simultaneously. The container is mounted on a radial disc type turret. The container rotates on its own axis to be printed. Then the turret rotates and the containers are then moved in order to place them under the next print head. The turret has two stations that serve to enter and exit the containers. In figure 7 it is evident how the topology works.

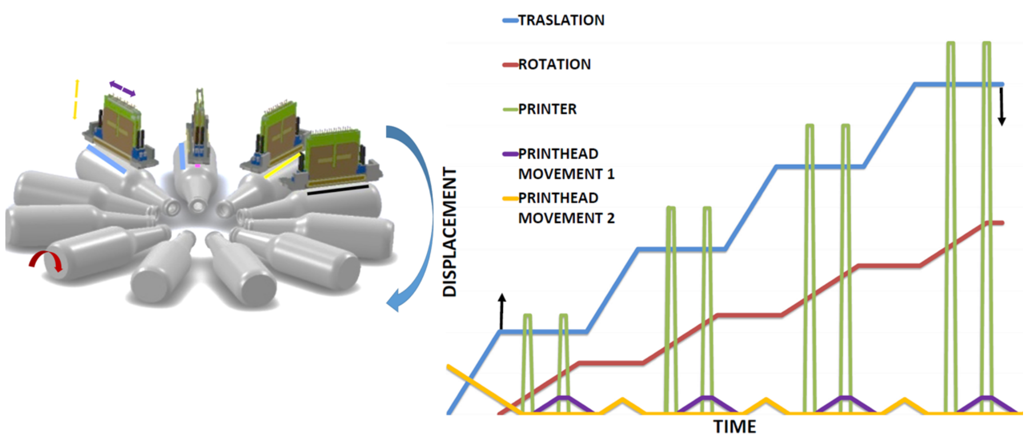

Figure 7. Topology 5

3.6. *Error in printing quality in topology 1*

In topology 1, the print quality is improved by increasing the number of nozzles per unit length of the printheads, but at the same time requires a greater precision in the precision of the mechanisms.

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The precision in the manufacturing demands that specialized machines be used (grinding machines, machines of measurement by coordinates, lapping) and cost efficient.

By selecting the topology that gets the best combination in precision, productivity and quality are analyzed. The magnitude of the error is found [26], which sums up all the elements together.

The magnitude of the error is found [25], which sums all elements together.

$$\varepsilon_i = \sqrt[p]{\sum_{n=1}^{k_i} (|Error_n|)^p} \tag{1}$$

κ_i: Number of elements of the topology i

ε_i: accumulated error topology i

$Error_n$: element error type n

p: values near 1 for optimistic estimations and values near 2 for conservative estimations

This topology 1 as an example Figure 8 is constituted by a functional structure, which begins with the feeding where the container is deposited in a support that is on a conveyor belt that moves it through the whole process. It then advances until it is under the first print head in the holding zone. two conical surfaces are located in the extremes of the container. To get the container centered, the surfaces is moved against the container using a ball screw mechanism [24] [6] once the container is held, the mechanism begins to rotate and the first print head begins to eject the ink. Once the first color is printed, the container is released and the conveyor belt is moved where the same printing process is repeated three times but with different print head color. Subsequently, the container is ejected from the printing line ending the printed process Figure 8.

The table 1, shows errors found in the analysis.

3.7. Error in printing quality in topology 2

This topology 2 as an example Figure 9 consists of a functional structure which consists of a support placed linearly one behind the other, when fed, a set of bars and wheels transmit the movement by turning the container continuously, while another transmission system is in charge of performing the linear movement that would pass through all the printheads. When entering the container, this is held by means of supports and upper rollers which guarantee stability and concentricity throughout the system.

The table 1, shows errors found in the analysis.

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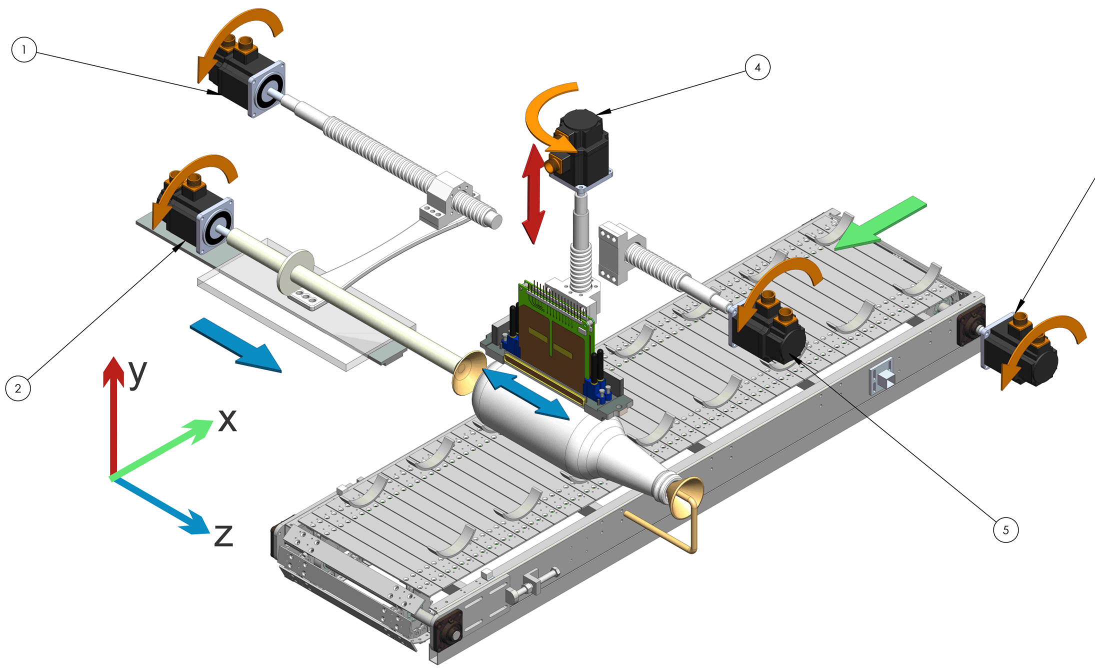

Figure 8. scheme topology 1

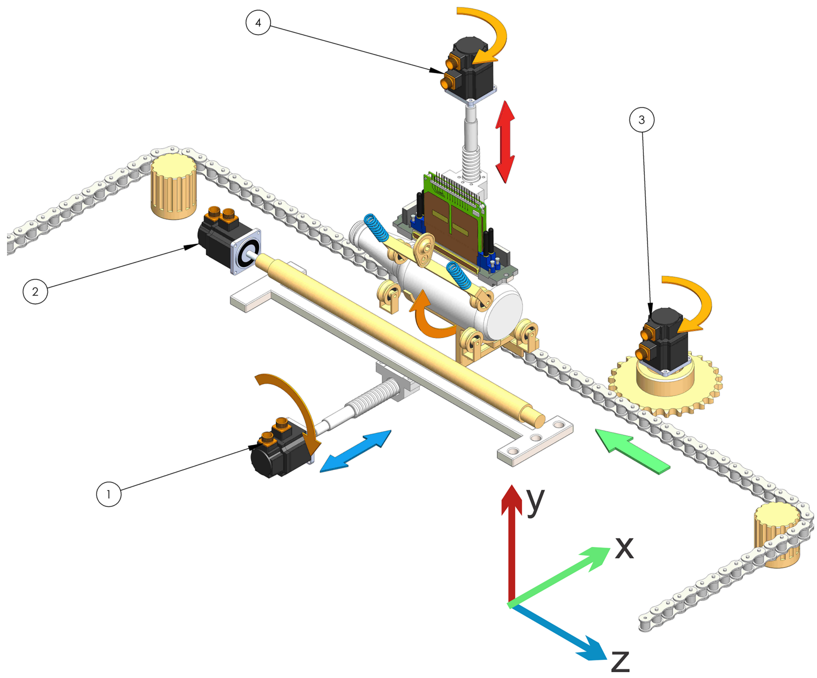

Figure 9. scheme topology 2

3.8. Error in printing quality in topology 5

This topology 5 as an example Figure 10 consists of a functional structure consisting of a shaft located vertically in the center of the main mechanism as a transmitter of the radial movement to the gears. In the lower part, there is a crown with internal bearings allowing the rotation of the mechanisms which are radially translating the container between the printheads. A gear facilitates the rotation of the container during a continuous printing process. During this process, the cam mechanism and spring hold and eject the container.

The table 1, shows errors found in the analysis.

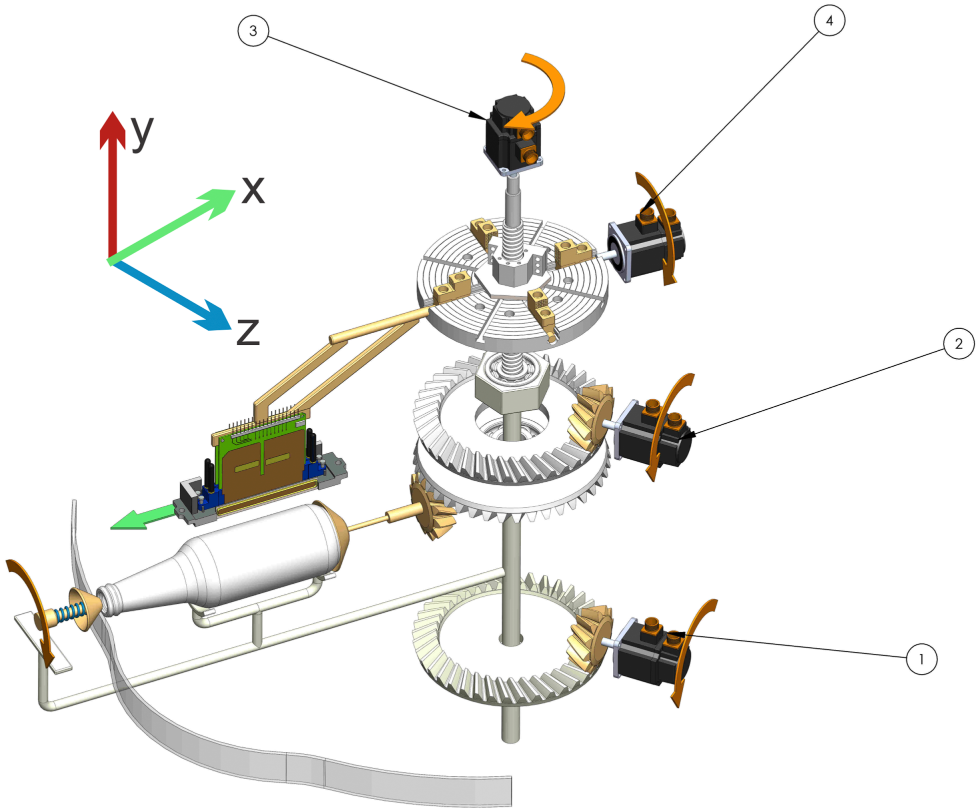

Figure 10. scheme topology 5

Table 1. Topologies Error

	Motor 1	Screw ball recirculanting 1	Motor 2	Motor 3	Band	Motor 4	Screw ball recirculanting 4	Motor 5	Screw ball recirculanting 5	Conical surfaces	total
Topology 1											
Rotation container			5	5	100						110
X container				5	100						105
Y container						5	50				55
Z container	5	50						5	50	250	360
Topology 2											
Rotation container			5								5
X container				5	100						105
Y container						5	50				55
Z container	5	50									55
Topology 5											
	Motor 1	**Crown Gear 1**	**Motor 2**	**Motor 3**	**Screw ball recirculanting 3**	**Motor 4**	**Chuck mechanism 4**	**Crown Gear 2**	**Cam Mechanims**	——	**total**
Rotation container			5					100			105
angular traslation	5	100									105
Radial traslation						5	50		50		105
Y container				5	50						55

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3.9. Print time

The productivity of a printing machine is defined as the printed output per unit time. Inkjet technology in printing still does not compete in productivity with the analog technologies (lithography, flexography, rotogravure, screen, dry offset), and from there comes the need to improve productivity [30] to perform comparable productivity with the analog technologies. To evaluate required for each stage of the topology printing are indicated in a relative and parametric way See figure 11. The standard time is called the time takes to print the container. All other times of the other activities are assigned a number relative to the standard value as follows:

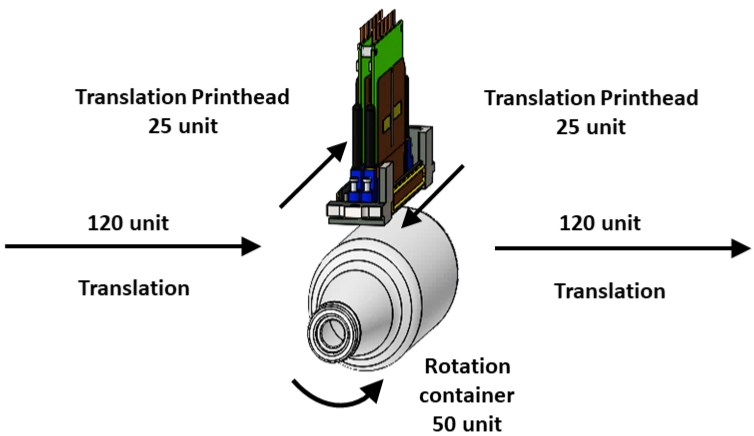

Figure 11. general print time process

the process overall time is defined to the time that takes to one container goes to one print head to another. Thus estimating, process time for one color:

process time for one color: PT Pinhead translation time: phtt container traslation time: ctt container rotation time: crt (note in this moment the print head is printing)

For topology 1 and 5

$$PT = ctt + crt + phtt + crt \tag{2}$$

for topology 2

$$PT = crt + crt \tag{3}$$

productivity = P Time unit= T

$$P = PT/T \tag{4}$$

4. Discussion and Conclusion

In this article was presented the qualitative design of a direct digital inkjet printer working over cylindrical substrates comparing five mechanical topologies; three topologies with radial distribution and two topologies with parallel distribution. The design criteria were precision as principal and productivity as complementary. The method used allows implements evaluable

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options. The adaptation of a flat printer to cylinder printing does not give a positive result due to the perpendicularity between the axis of the container and the axis of the print head.

Cylindrical printing machines demand a high level of accuracy, that is way this are classified within a similar condition that light machine tools. For inkjet printing, the optimal topologies are oriented to machines with simultaneous printing because it can get closer to the high productivity of others printing technologies (for example flexographic). The main non-accuracy occurs when the container is released to be transported from one station to another, increasing the synchronization color error. One of the challenges in the design is to minimize the errors when the container is longer than the print head and it is required the movement of printing in Z direction be extended including one axis more. The minimum error was found in topology 2, topology 5 had the second place and topology 1 has the most amount errors. The most productive machine, topology 2, has the lowest rating error during the displacement of the container between stations. The topology 2, then qualifies as a high efficiency machine but the software and file management between print heads need to be developed due to the figure in the file is no the same than the figure over the container. At the moment the commercial offer of machines for inkjet printing is low and due to the new technology, the manufacturers offer is low. As finally result we considered for Future work focuses on building a detailed mathematical and 3d model to optimize the conceptual design.

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