NUMBER AND TYPE SYNTHESES FOR AN ONE-SIDE STITCHING DEVICE

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Abstract. *The design of new mechanical devices depends on the designer's experience and knowledge. Design methodologies were created in an effort to make the designing process less dependent on the designer. In this work, a few mechanism design methodologies are analysed and compared. Then, a new methodology is proposed, concentrating on the determination of structural and design characteristics for the elimination of unfeasible mechanisms.*
Many researches were made in the field of stitching mechanisms. Such mechanisms can be classified in two types: two-side access and one-side access. This last one has a great potential for many applications, such as textile industries, stitching composite materials and suturing in endoluminal surgeries. However, few of such devices were successfully developed. In this work, a state of the art survey for one-side stitching mechanisms is done. Through survey analysis, a list of structural and design requirements for the cited mechanism is done. Finally, using the proposed methodology and the listed requirements, it is done the number and type syntheses for one-side stitching device's mechanisms.

Keywords: *number and type syntheses, one-side stitching, mechanism synthesis, mechanism design methodology, stitching devices*

1. INTRODUCTION

Nowadays, great efforts have been done to design faster, better and more innovative products. Design methodologies are important tools to achieve such goals. Therefore, the first step to design a product is to select an appropriated design methodology.

In the field of mechanism design, several methodologies were developed, such as those by Hartenberg and Denavit (1964), Yan (1999), Tsai (2000) and Simoni (2010).

Hartenberg and Denavit (1964) divides the process of desiging a mechanism in three steps: number synthesis, type synthesis and dimensional synthesis. Number synthesis consists in how the links are connected to each other and its effects on the kinematic chain's mobility. Type synthesis determines the type of the kinematic pairs, *i.e.*, which degrees of freedom (DOF) each kinematic pair has. Dimensional synthesis determines the links' dimensions. When compared to recently developed mechanism design methodologies, such as Yan (1999) and Tsai (2000), Hartenberg and Denavit (1964) is very simple and lacks some important steps, as making a state-of-the-art survey and establishing the design requirements. However, the three steps presented by Hartenberg and Denavit (1964) are recurrent in other mechanism design methodologies, thus, its understanding is important.

More recently, Yan (1999) has presented a methodology that uses concepts of graph theory and combinatorial analysis. Yan's methodology includes a state-of-the-art survey, which is used to determine the design requirements. Once such requirements are specified, the synthesis is done, resulting in all possible chains which have the same structural characteristics of those found in the survey. This methodology is more straightforward; however, it is also limited to what is found in the survey.

Similarly to Yan's methodology, the methodology proposed by Tsai (2000) uses graph theory and combinatorial analysis to enumerate mechanisms. However, Tsai (2000) recognizes that mechanism design is an iterative process. In addition, Tsai's methodology considers design optimization, computer simulation, prototype demonstration, documentation and production phase.

In this work, concepts of the cited methodologies are studied and a new methodology is proposed, focusing on the determination of design requirements and how such requirements can be used to eliminate unfeasible kinematic chains and mechanisms.

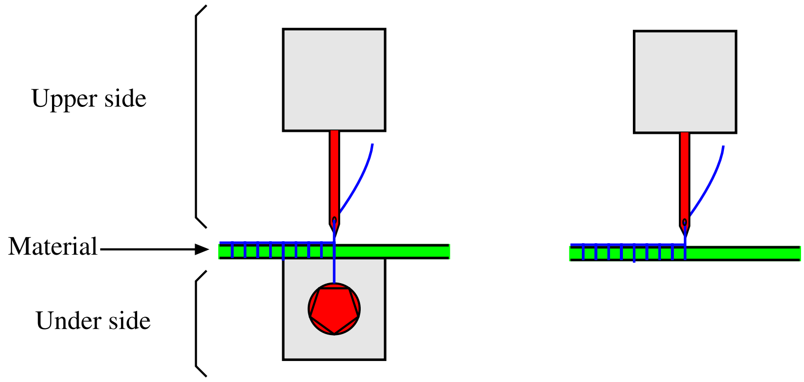
The proposed methodology is applied on the problem of stitching with one-side access and three innovative mechanisms are presented as solutions.

The stitching device's function is to join two or more parts using threads. Within this function, a wide range of materials can be used for the parts and the threads as well as many types of stitches are available to choose (Udakhe and

Basuk, 2011).

When compared to screws, nails and staples, stitches are cheaper and lighter. In addition, stitches can be continuous, thus, the joining strength is more uniform along the joint and the joint has some sealing capabilities. Other seam characteristic is that the joint remains flexible, allowing the stitched surface to bend. Such bending characteristic is desirable in some applications as in clothing and constructing flexible ducts.

A stitching device can be classified in: two-side stitching device (2-SSD) and one-side stitching device (1-SSD). On a 2-SSD, the device's parts are on both upper and under side of the material, as exposed in Fig. 1a. On an 1-SSD, the device's part is located only on one material's side, the upper side, as exposed in Fig. 1b.



(a) 2-SSD. (b) 1-SSD.

Figure 1. Example of two-side stitching device and one-side stitching device.

The variety of stitches for 2-SSDs is larger than those for 1-SSDs; therefore, the application field for 2-SSDs is wider. However, there are some applications that requires an 1-SSD, such as stitching a closed surface. A few applications for an 1-SSD will be exposed in Sec. 3.1 Finally, the authors noticed that in comparison to 2-SSD, 1-SSD is a field that remains underexplored.

In this work, the problem of stitching with one-side access will be studied. Then, using the proposed methodology, three innovative mechanisms for an 1-SSD are presented.

2. MECHANISM DESIGN METHODOLOGIES

Mechanism design methodologies assist the designer to create new mechanisms. The first step of a design process is to select the appropriated methodology. However, there are several mechanism design methodologies. In this section concepts of three methodologies will be exposed, as well as their advantage and disadvantage. More informations about each methodology can be found in the respective cited works.

2.1 Methodology proposed by Hartenberg and Denavit (1964)

Hartenberg and Denavit (1964) identifies three stages in the process of mechanism design: type synthesis, number synthesis and dimensional synthesis. These steps appear in other mechanism design methodologies and they can be combined, interrelate or using an additional tool, such as graphs.

Type synthesis determines what types of kinematic pairs will be used. Example of types of kinematic pairs are revolute, prismatic, cam and gear. Hence, type synthesis dictates which degrees of freedom each kinematic pair will have.

Type synthesis is a combinatorial problem, *i.e.*, given the types of pairs and the number of kinematic pairs, it must be determined all combinations of types of pairs and kinematic pairs. As the number of combinations grows fast in combinatorial problems, it is useful to reduce the number of types of pairs. The determination of the available types of kinematic pairs is affected not only by kinematics. External factors, such as available materials, manufacturing process and the specific mechanism application, can be used to restrict the types of pairs and reduce the quantity of results.

Number synthesis aims to enumerate all possible kinematic chains that satisfies the design requirements. First, it is selected a group of three structural characteristics, such as the number of independent loops (ν), the screw system's order (λ) and the kinematic chain's mobility (M). Then, the number of links (n) and kinematic pairs with one degree of freedom (j) can be calculated using the mobility equation,

$$M = (n - 1 - j)\lambda + j, \tag{1}$$

and the Euler equation,

$$\nu = j - n + 1. \tag{2}$$

Once the number of links and kinematic pairs have been determined, the partitions can be found by determining the number of elements of kinematic pairs in each link. Then, for each partition all possible kinematic chains are enumerated. More details on the enumeration of the kinematic chains and mechanisms can be found in Simoni and Martins (2007) and Simoni *et al.* (2011).

Dimensional synthesis determines the links' lengths. As the objectives of this work are number and type syntheses, this work will focus on type and number syntheses. Further details about dimensional synthesis can be found in Hartenberg and Denavit (1964).

Besides the great contribution for mechanism synthesis made by Hartenberg and Denavit (1964), the lack of a formal definition for the design steps makes the work of Hartenberg and Denavit (1964) rather a guideline than a methodology.

2.2 Methodology of Yan (1999)

The methodology proposed by Yan (1999) is based on the structural requirements' determination using a state of the art survey and on the representation of kinematic chains by graphs. Also, Yan's methodology foresees the use of permutation groups to eliminate isomorphic solutions from the number synthesis.

Yan's methodology proposes a state of the art survey. Such survey must list all devices that solve the proposed problem or a similar problem. The devices of the list are analysed and their structural characteristics are used to proceed with the synthesis of kinematic chains. Thus, this methodology generates all kinematic chains whose structural characteristics are the same of those mechanisms found on the survey.

In this methodology, the input data of the number synthesis step are the number of links and kinematic pairs. Hence, as the designer does not need to determine directly the the number of circuits and the screw system's order, Yan's methodology is more straightforward.

However, Yan's methodology does not foresee the case when the number of independent loops or the screw system's order is known. Also, as the structural requirements are generated through the survey, this methodology is limited by the already existing devices.

2.3 Methodology of Tsai (2000)

The methodoloogy proposed by Tsai (2000) is similar to that proposed by Yan (1999). However, the structural requirements used to make the number synthesis are not limited by the state of the art survey. Also, Tsai (2000) considers the use of two engines, a generator and an evaluator.

The generator synthesizes the kinematic chains based on a set of structural requirements. Other structural and design requirements are used by the evaluator to analyse the generated kinematic chains. When necessary, the structural requirements used in the generator can be changed. Thus, generator and evaluator work on an iterative process until feasible results are found.

In relation to Yan's methodology, Tsai's methodology has the advantage of not relying only on the survey to determine the requirements. Also, the iterative process of the generator and evaluator can be used as an optimization process. For example, if some structural characteristics is not well-defined, then it can be used as a design variable; therefore, according to the evaluation of the results, an optimum value can be found for the design variable.

2.4 Other mechanism design methodologies

Besides the three methodologies presented in Sec. 2.1 , 2.2 and 2.3 , there are other methodologies, such as those presented by Tischler *et al.* (2001) and Simoni (2010). Each methodology has its vantages and disadvantages, however, only three were presented in order to be brief.

2.5 Proposed methodology

The proposed methodology combines some aspects of the Yan's and Tsai's methodologies.

First a state of the art survey is done. As in Yan's methodology, the goal for this survey is to list all devices that solve the proposed problem. However, the survey also serves as a guideline in the designer's decisions and to give the designer a better understanding of the problem.

The devices in the survey must be analysed and have their screw systems identified. This guides the designer to choose an appropriate screw system. It is important that the chosen screw system must generate the desired motion between the points of interest and the fixed link, *i.e.*, the screw system is determined by the desired motions. This excludes screw systems that are not feasible, lasting just a few screw systems. Which screw system will be used is upon the designer. The higher the screw system's order, the more results number and type synthesis will generate. Also, such kinematic chains will be more complex. However, the lower the screw system's order the more restrictions the kinematic chain will have, thus, the designer must be careful regarding redundant restrictions (Reshetov, 1982).

As the screw system is capable of generate the desired motion, a solution exists. However, the complexity of the desired motion will affect the complexity of the mechanism. The number of independent loops of a mechanism can be considered as a measure of its complexity. Therefore, when the number of independent loops is not well-defined, it can be adopted the lowest value possible for it and, if the results are unfeasible, then the number of independent loops can be increased.

In general, the mechanism's mobility is known. If not, then the survey can help the designer to determine the mobility.

Other characteristics may be notice when analysing the survey's devices. It is important that the designer keeps them in mind during the synthesis process. Since the design of mechanisms involves combinatorial problems, it is usual for the number of results grow fast. Thus, the designer must use the design requirements to exclude unfeasible results.

Yan (1999) seeks innovation by synthesizing mechanisms whose structural characteristics are the same to those on the survey. However, innovation can also be found using a different set of structural characteristics. Also, the designer must search for desirable characteristics that do not appear on the survey, such as the best way to operate, maintain, assemble, disassemble and manufacture the device. All interaction that the device will have with humans or machines must be analysed.

Once all mechanism are enumerated, the most promising ones must be selected to continue on the design process. Then, type synthesis is done. Structural and design characteristics can be used to guide the type synthesis and reduce the number of results.

After the type synthesis, dimensional synthesis and design optimization must be done. Then, simulations in CAD software and prototypes are done. When necessary, any adjustment can be made. Then the process of documentation and patent are done and the device enters in manufacturing phase.

More details on the proposed methodology is shown in Section 3, where the proposed methodology is applied.

3. STITCHING DEVICES

As said in Sec. 1, this work aims to solve the problem of stitching with one-side access. First, examples of application for an 1-SSD are presented. Then, according to the methodology proposed in Section 2.5, a state of the art survey is made and the devices are analysed. Finally, through the analysis of the existing solutions, structural and design requirements are listed.

3.1 Applications of one-side stitching device

Two-side stitching devices and 1-SSD have different but not fully distinct applications. Two-side stitching devices can make more complex stitches; however, in some applications the use of an 2-SSD is difficult or impossible.

Stitching closed surfaces is impossible with 2-SSD since there is no access to the inner side. Also, depending on the direction of the stitch, open slenderness surfaces can also be difficult to stitch with an 2-SSD. In these cases, an 1-SSD is necessary.

There are several examples of application for an 1-SSD in industry, such as closing tubular tyres, stitching industrial filters and general textile industries products.

Other application for 1-SSDs in textile industries is to optimize the manufacture line. When stitching a garment, the seams must be done in such an order that allows all the seams to be done. For example, consider the sleeve of a baby's shirt stitching process. When the longitudinal seam is done first, generating the cylinder aspect of the sleeve, it might be impossible to make the hem. Thus, the hem must be done first and then the sleeve is closed. When an 1-SSD is used, it is possible to make the sleeve, regardless the seam's order. Thus, the use of an 1-SSD makes the manufacturing line more flexible.

In high technological field, the adoption of composite materials in becoming more frequent. However, shaping such materials in the desired form can still be a difficult task. One method to shape composite materials is stitching its layers together. Such method has the advantages of being quick, simple and low cost (Zhao *et al.*, 2009). Nevertheless, to be able to stitch complex forms it is necessary to use an 1-SSD (Brandt *et al.*, 2001; Wittig, 2001).

Medicine is also a promising field of application for an 1-SSD. Minimally invasive procedures uses differentiated techniques and tools to perform surgeries with minimum damage to the patient's body. In comparison with regular procedures, minimally invasive has lower recovering time, probability of having an infection, loss of blood and mortality rate (Saadi *et al.*, 2006). Endoluminal surgeries are minimally invasive procedures and uses the human body's empty internal volumes to execute medical procedures. Many breakthroughs have been done lately in this field, not only in technique but also in materials and tools (Verdonck, 2008). To perform an endoluminal surgery, it is necessary to insert catheters containing the tools into the patient. Therefore, the tools must be miniaturized. In addition, as the surgery uses empty internal volumes, any procedure must be done only with one-side access. Thus, when it is desired to perform a stitch, the device must be an 1-SSD.

3.2 State of the art survey

According to the methodology proposed in Sec. 2.5 , a state of the art survey was done. However, this section will present only some characteristics found and a few examples.

First, it is necessary to understand how a generic 1-SSD works. An 1-SSD requires the thread to be passed from one side (side *a* in Fig. 2) to the other (side *b*) and then return to the first side (side *a*); therefore, the needle passes through points *1*, *2*, *3* and *4* in Fig. 2, respectively. This thread's motion is done by the needle, which carries the thread.

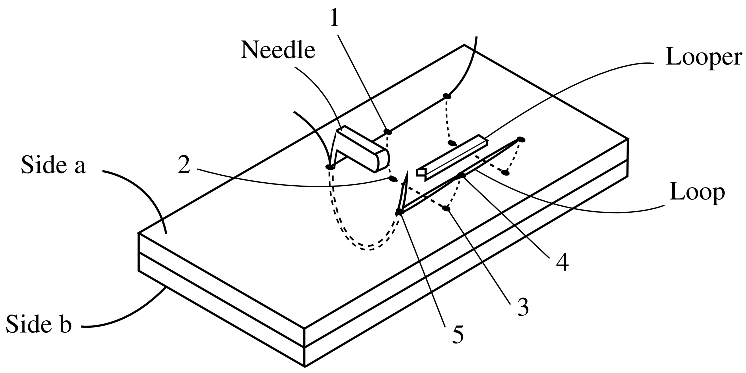


Figure 2. Stitch formation.

As the needle and the thread reach side *a*, they pass inside a loop formed previously. Then, the thread must bend to make the next loop. The thread of the next loop is caught by the looper. Notice that for the device be an 1-SSD, the looper must remain on the same side of the needle.

Once the loop is caught, the needle returns from side *a* to side *b*, passing through points *4*, *3*, *2* and *1*, respectively, reaching side *a* again. Since the needle is off the material, the whole device can advance to the next stitch's location. Such advance can be done in any way that suits the application. For example, when stitching layers of composite the 1-SSD is mounted on a robot arm, which is responsible for the advance. Once the 1-SSD advances, the process repeats: the needle passes through the material and inside the previous loop, the next loop is formed and the looper grabs it.

3.2.1 Needle types considerations

For the device to be an 1-SSD, the thread's tips must remain on the same side. Thus, either the material being stitched or the needle must be curved (as exposed in Fig. 2). Examples of 1-SSDs that curves the material are presented by Moll and Schlondorff (1988) and in the first embodiment of Yamamoto and Chung (2007). Examples of 1-SSDs that use a curved needle are presented by Keilmann (2002) and in the second embodiment of Yamamoto and Chung (2007).

Another possibility is to use a straight needle and a straight looper. In this configuration, the needle would puncture the material and take the thread to side *b*. Then, the looper crosses the material and grabs the loop on side *b*. The devices RN 820 by Altin and RS 530 by KSL use straight needle and looper (Thurm, 2004; Koissin *et al.*, 2006). However, this configuration has the disadvantage of catching the looper in an unknown environment. When the 1-SSD is used in endoluminal surgeries, an organ could be on side *b* or it could have fluids flowing on side *b*. As the handle of the loop is a critical phase, it is desired that such handle be done in a known environment. In addition, an 1-SSD that uses straight needle and looper cannot perform blind stitches.

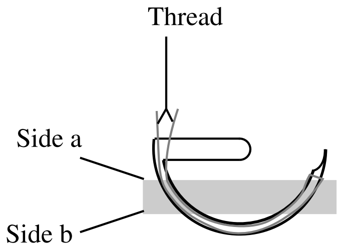
When the material being stitched is curved, it is possible to use a straight needle. However, it would restrict the device's applications, since in some applications it is difficult or impossible to bend the material. Therefore, a design requirement is that the needle must be curved, not the material.

Regarding the use of a curved needle, three types of curved needle were found.

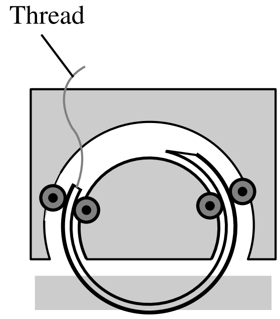
Simple curved needle (SCN): this is the simplest form of curved needle found in the survey. It is composed of a solid piece that remains connected to the device in only one way during the operation. The needle rotates in a rocking motion, moving along sides *a* and *b*. The device proposed by Keilmann (2002) uses a SCN. Figure 3a exposes a generic SCN.

Floating curved needle (FCN): this needle is capable of rotate indefinitely. The power can be transmitted to the needle in a few different ways, such as using friction wheels (Adami *et al.*, 2008) or ratchets (Stokes *et al.*, 2007). An example of FCN is shown in Fig. 3b.

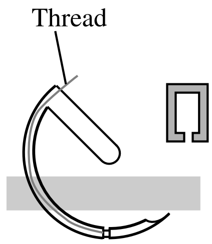
Needle holder system (NHS): in this concept, the needle is composed of two parts, a needle and a needle holder. The thread is tied to the needle, and the needle is pushed from side *a* to side *b* and back to side *a* by the needle holder. Once the needle is on side *a*, the needle is passed to a second needle holder. Then, the first needle holder returns to the initial position on side *a*. The needle is passed from the second needle holder to the first and the process repeats. This type of needle is used by Rioux and Sauvageau (2004). Figures 3c and 3d show this type of needle in two different stages during the operation.



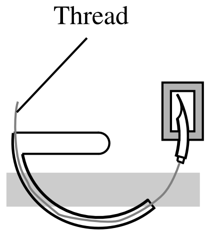
(a) Simple curved needle.



(b) Floating needle.



(c) Needle holder I.



(d) Needle holder II.

Figure 3. Types of curved needle.

The FCN is less reliable when compared to the SCN. The FCN presents difficulties regarding its actuation. Frictional wheels allows sliding between the wheel and the needle. Also, external fragments or even fragments from the material could enter between the wheel and the needle, affecting the needle's actuation. Ratchets allows rotation in only one direction. In addition, ratchets needs to be larger in order to contain the teeth, resulting in more damage to the material. Finally, the SCN is more rigid, more precise and has less components than FCN.

The NHS also presents drawbacks when compared to SCN. The major disadvantage of the NHS is to guarantee that the needle be secured in both needle holders and be correctly passed from one needle holder to another. Also, as the needle holder has to secure the needle, the needle holder tends to be large, which can be seen in Rioux and Sauvageau (2004) and in Badhwar (2011). The result is that the needle's cross-section in NHS is larger then in SCN; thus, NHS produces more damage to the material than SCN.

Considering the presented drawback of the FCN and NHS, a design requirement is that the needle be a SCN. In addition, the radius of the curvature of the needle must be constant, so it does minimum damage to the material. Finally, the motion of the needle must be rotative, with the axis of rotation passing on the center of the needle curvature.

3.2.2 Feasibility of 1-SSDs implementation

According to the survey, the only 1-SSD using SCN that achieved some commercial success is the stitching head RS 510, developed by KSL GmbH (Brandt *et al.*, 2002). This device's mechanism is patented by Keilmann (2002) and is exposed in Fig. 4.

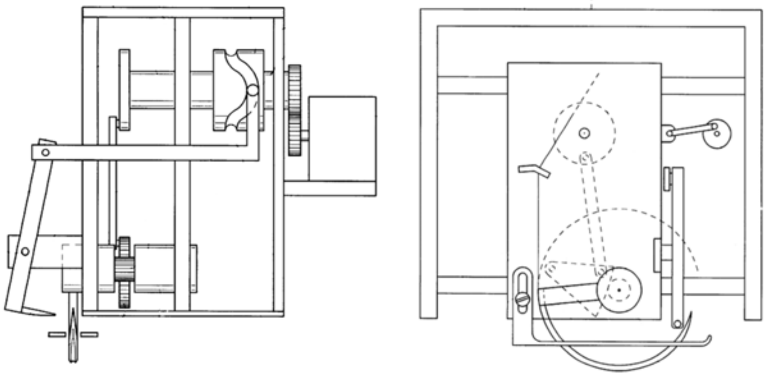
Analysing the device proposed by Keilmann (2002), it is noted that its design is simple and has a low quantity of links. Although there are higher kinematic pairs, since the application does not require miniaturization, such pairs are not difficult to manufacture.

Several patents, such as Badhwar (2011), Stokes *et al.* (2007) and Adami *et al.* (2008), Nomoto *et al.* (1984), Yamamoto and Chung (2007), presents complex solutions. In those patents, it was noticed at lest one of the following drawbacks: high number of links; high number of kinematic pairs; type of kinematic pair was hard to manufacture when miniaturized; the device perform a complex type of stitch; the mechanism was complex, *i.e.*, with a high number of independent loops.

Therefore, it is a design requirement that the device has the lowest possible number of links, kinematic pairs and independent loops and, when miniaturized, the kinematic pairs must be easy to manufacture and still work properly.

3.2.3 Considerations about catching the loop

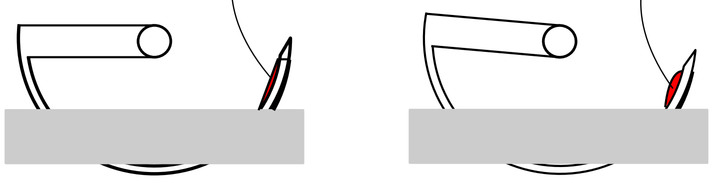
A critical step during the stitching process is grabbing the loop. The farther the thread is from the needle, the easier it is for the looper to grab it. As shown in Fig. 5, the thread is farthest from the needle when the needle has just begun its



(a) Front view. (b) Side view.

Figure 4. RS 510 patent. Adapted from Keilmann (2002).

returning. In this moment, the threat is compressed and it bends away from the needle, as shown in Fig. 5b.



(a) Needle at end of trajectory. (b) Needle starts returning.

Figure 5. Formation of the loop area.

Notice that when the thread is bent, it is farther from the needle than when the thread is strained (see Fig. 5a). Loop area can be defined as the area between the thread and the needle, measured on the plane normal to the needle's axis of rotation. Thus, as the loop area is larger in situation depicted in Fig. 5b, a design requirement is that the device grabs the thread in the mentioned situation.

The easiest way for the looper to catch the thread of the loop is performing a motion perpendicular to the plane of the loop area (see Fig. 6). The looper can have any motion, as long as it crosses the mentioned plane perpendicularly and the thread remains attached to the looper. In Fig. 6 two possible motions for the looper are shown, motion *a* is a translation and motion *b* is a rotation.

3.2.4 Considerations about the screw system for an 1-SSD

According to the methodology proposed in Sec. 2.5, the mechanism of the devices found in the survey were analysed in order to determine the necessary motions for the needle and the looper.

The screws representing the needle's and looper's motions, according to Sec. 3.2.1 and 3.2.3 , respectively, are represented in Fig. 7. The screw $\$_0$ represents a screw with pitch zero, *i.e.*, a rotational motion around axis z. The screw $\$_\infty$ represents a screw with infinite pitch, *i.e.*, a translation along axis z. For more details on screw systems and screw theory see Hunt (1978).

Hunt (1978) and Tischler (1995) emphasize the importance of using a screw-system that guarantees full-cycle mobility. When the screw system guarantees full-cycle mobility, any proper mechanism in a general position will maintain its mobility. However, in some special configurations the mobility can change. When the screw system does not guarantees full-cycle mobility, the dimensional synthesis must be carefully done to achieve the desired mobility. Thus, in the second case, the design process is very restrict and a solution that satisfies the design requirements is unlikely to exist.

According to Hunt (1978), there are nine screw systems that guarantees full-cycle mobility (including the general six-system). The chosen screw system must allow the motions of the needle and the looper to be done; therefore, the screws represented in Fig. 7 must be generated by the screw system.

Considering those nine screw-systems, eliminating the screw-systems that do not generate the desired motions, four screw systems remain: the fifth special two-system, the second-special three system, the third special four-system and the

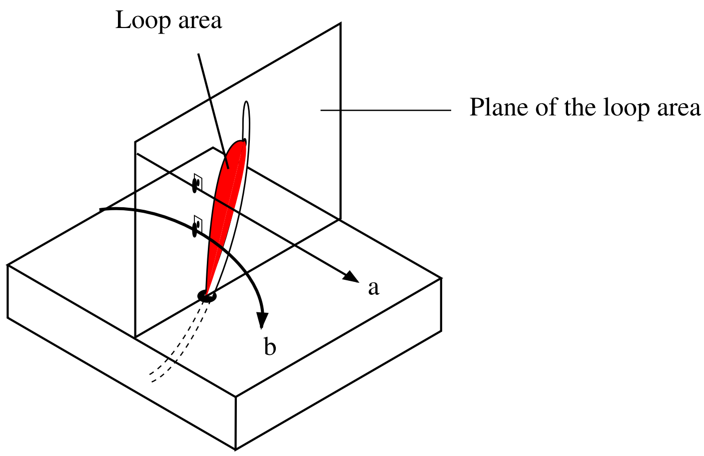


Figure 6. Motion for catching the loop.

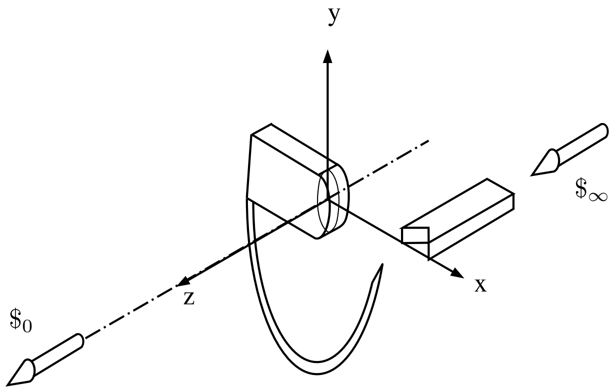


Figure 7. Desired motions for the needle and the looper of an 1-SSD.

general six-system.

Choosing a screw-system with a higher order than needed implies in more results for the number synthesis; thus, the combinatorial analysis effort in the number and type syntheses is increased. Therefore, it is chosen the fifth special two-system. Also, according to a survey done on two-system mechanisms, with the exception of planetary gear train exposed in Cazangi and Martins (2007), no other device uses a two-system.

Once the screw-system is chosen, the looper's motion can be re-analysed. On the chosen screw-system, the only possible motion for the looper that will cross the plane of the loop area perpendicularly is a translational motion along axis z. Therefore, the motion of the looper is a translation along z.

3.2.5 Mobility of an 1-SSD

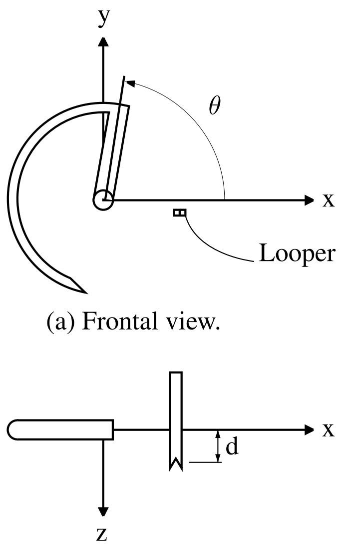
According to Sec. 3.2.4, the needle performs a rotative motion around axis z and the looper perform a translational motion along axis z. The needle's and looper's displacements parameters are defined in Fig. 8. Functions of θ and d are shown in Fig. 9, in which the time scale is in relation to the period T (time to perform one stitch).

The needle's and looper's motions must occur synchronously, *i.e.*, every needle's position corresponds to a looper's position. Therefore, a single mobility is necessary to control the stitching device (called the *main mobility*). However, as mentioned in Sec. 3.2.3 a critical phase is grabbing the loop. Depending on the application, external forces may acts on the thread, such as fluid flow, affecting the formation of the loop. Also, when different thread's materials and diameters are used, the loop's formation might be affected as well. Therefore, it is desirable that the mechanism has some synchronization adjustment between the needle's and looper's motions. Hence, a mobility is added to the system, called the *adjustment mobility*.

3.2.6 Structural and design requirements

In according to what was presented about the needle's and looper's motions, both of these end-effectors can be connected directly to the fixed link through a revolute and a prismatic pair, respectively.

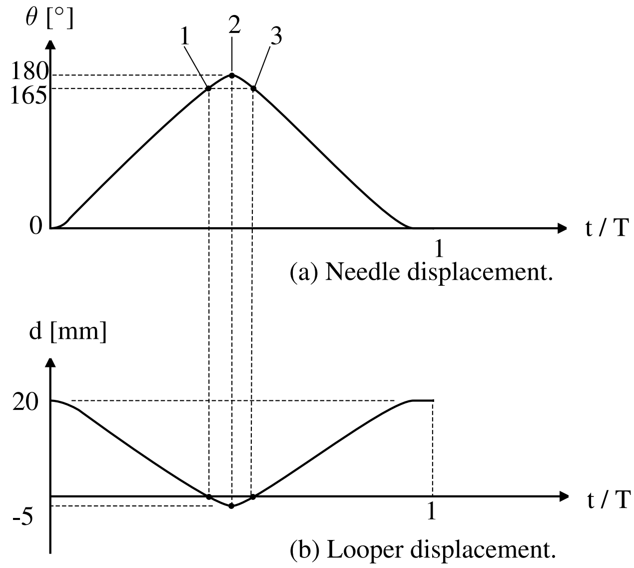
Regarding the actuators, notice that when they are placed on the pairs that connects the needle to the fixed link and the looper to the fixed link, each actuator will control only one end-effector; thus, there would be no need for a mechanism, no



(a) Frontal view.

(b) Top view.

Figure 8. Parameters for the displacements of the needle and the looper.



(a) Needle displacement.

(b) Looper displacement.

Figure 9. Displacements of the needle and the looper.

main mobility and no adjustment mobility. Hence, this placement for the actuators is forbidden as well as any placement that results in each actuator controlling one end-effector.

In addition, it is desirable that the actuators be placed on the fixed link, which implies on the fixed link be at least ternary.

A list of structural and design requirements is now presented:

- the order of the screw system is two;
- the screw system selected is the fifth special two-system;
- the mobility of the mechanism is two;
- the number of independent loops will be two;
- the needle's link must be connected to the fixed link by a revolute pair;
- the looper's link must be connected to the fixed link by a prismatic pair;
- the degree of control between the needle's and the looper's links is two;
- the actuators must be placed on the fixed link;

- the fixed link must be at least ternary;
- the actuators must be placed on the kinematic pairs whose freedoms are easy to be actuated.

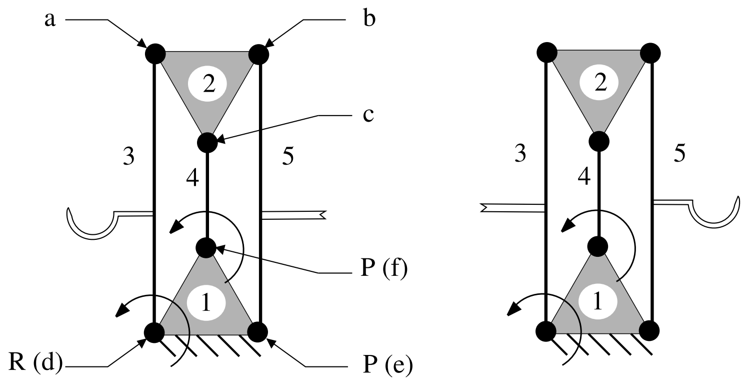
4. SYNTHESIS OF AN ONE-SIDE STITCHING DEVICE

Following the proposed methodology and according to the design requirements, number and type syntheses are done.

4.1 Number synthesis

The enumeration of the kinematic chains was manually done using Farrell's method. For more details of the method see Simoni and Martins (2007), Simoni *et al.* (2009) and Simoni *et al.* (2011). The structural requirements used in the number synthesis was the screw system's order, the kinematic chain's mobility and the number of independent loops, as presented in Sec. 3.2.6

The number synthesis yields two partitions and a total of three proper non-isomorphic kinematic chains. For each chain, all mechanisms were enumerated. Also, for those mechanisms, all combinations for actuators' and end-effectors' placements were analysed. Excluding the unfeasible mechanisms, only one mechanism with two different placements for the actuators lasts. The two feasible results are exposed in Fig. 10. Notice that the mechanisms shown in Fig. 10 have mobility two since they are not planar mechanism, *i.e.*, the screw system is the fifth special two-system.



(a) Actuator on needle. (b) Actuator on looper.

Figure 10. Feasible results for an 1-SSD.

Notice that the needle needs to puncture the material and the looper needs to catch the thread. The forces acting on the needle tend to be larger than those acting on the looper. When mechanism from Fig. 10b is chosen, the power necessary to puncture the material will be transmitted through links 2 and 3; thus, such links and their kinematic pairs must be design to stand such power. However, when mechanism two is chosen, the power for the needle to punctures the material comes directly from the needle's actuator; thus, there are less forces being transmitted through the mechanism. Therefore, mechanism from Fig 10a is chosen.

4.2 Type synthesis

The fifth special two-system only generates screws of infinite pitch with axis parallel to axis z and screws with any pitch whose axis is concentric with axis z. Hence, the possible kinematic pairs are revolute (R), prismatic (P) and helical (H).

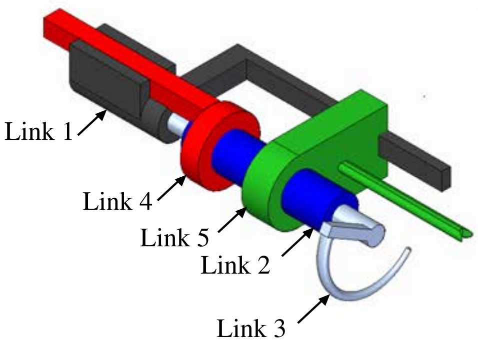
The arrange of the three kinematic pairs' types among the six mechanism's kinematic pairs from Fig. 10a, yields 729 possible combinations. However, at least a helical pair is needed to correlate the needle's rotation with the looper's translation. Also, the pairs connecting the needle and the looper to the fixed link are known. The pair connecting links *1* and *4* is chosen as a prismatic, since it is easy to be actuated, adjusting the synchrony of the end-effectors. The choice of these pairs' type are exposed in Fig. 10a. Considering the type of the cited pairs, only 19 possibilities remains.

Analysing all 19 possibilities and considering the design requirements, three mechanisms were found feasible and more promising. Table 1 exposes the pairs' types of the three feasible mechanisms, according to Fig. 10a. Figure 11 exposes *CAD* models for the solutions. As the dimensional synthesis depends on the application, the devices' dimensions in Fig. 11 are generic. Figure 11a shows the mechanism's assembled view, the exploded views of mechanisms *1*, *2* and *3* are shown in Fig. 11b, 11c and 11d, respectively.

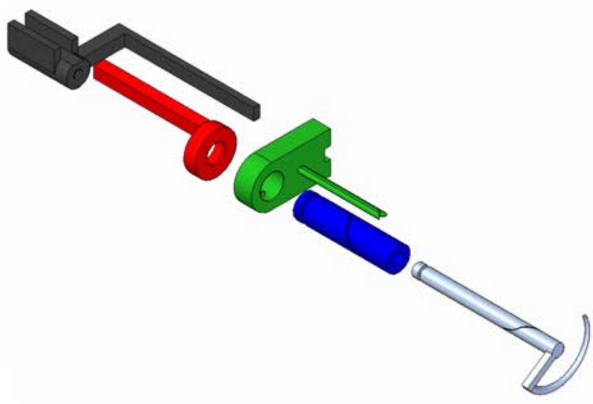
Mechanism two and three have the advantage of using only one helical pair, making its dimensional synthesis and manufacture easier than mechanism one. Mechanism one presents no great advantage in comparison with mechanisms two and three. The selection of which mechanism will be used on dimensional synthesis is upon the designer and it

Table 1. Types of kinematic pairs of the three feasible mechanisms.

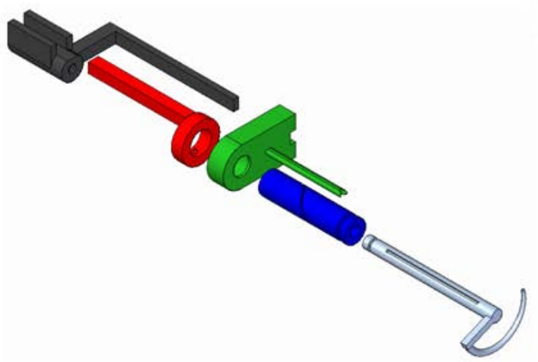
Mechanism	1	2	3
Pair a	H	P	P
Pair b	H	R	H
Pair c	R	H	R



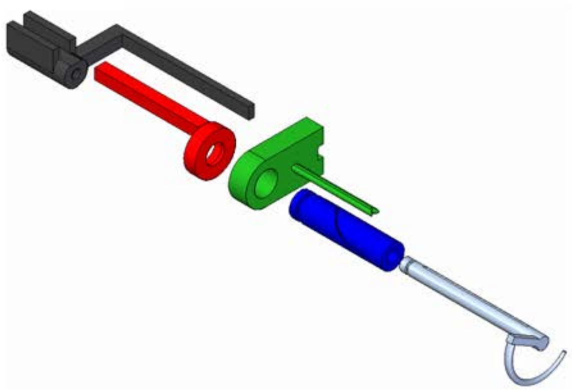
(a) Assembled device.



(b) Exploded view of mechanism 1.



(c) Exploded view of mechanism 2.



(d) Exploded view of mechanism 3.

Figure 11. Generic solutions of a mechanism for an 1-SSD.

depends on the 1-SSD's application. In all mechanisms, the main mobility (on pair *d*) must have a rocker motion, which can be done by any means suitable for the specific application. Also, the prismatic pair on *f* is the adjustment mobility, and can be actuated by any convenient mean. Finally, it is noticed that these three mechanisms are innovative, *i.e.*, no device on the survey uses such mechanisms.

5. CONCLUSIONS

The methodology proposed was used to make number and type synthesis for an 1-SSD. Since the mechanisms resulted from the syntheses process were unforeseen on the survey, the methodology succeeded to generate innovative results. Also, the methodology proved to be efficient, specially in determining the structural and design requirements. Such requirements were useful to generate and evaluate mechanisms for 1-SSD, aiding to identify feasible and promising solutions.

An extensive state of the art survey for 1-SSD was done, and it was used as guideline for the synthesis of a new and innovative 1-SSD. The proposed methodology was applicated to the problem of stitching with one-side access, resulting in three generic and innovative mechanisms for 1-SSD. The presented solutions' dimensional synthesis is left to be done, since it will depend on the specific application of the 1-SSD. Finally, it is noted that the presented mechanisms use the fifth-special two-system and, according to a survey on two-system mechanisms, the three mechanisms presented are the only ones that uses such screw system.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Adami, C.A., Calvi, R., Patorno, L. and Tuscano, G., 2008. "Device for sewing elements that can be sutured". US Patent 2008/0177289 A1.

Badhwar, V., 2011. "Automatic suturing apparatus and methods of use". US Patent 2011/0270279 A1.

Brandt, J., Drechsler, K. and Filsinger, J., 2001. "Advanced textile technologies for the cost effective manufacturing of high performance composites". In *RTO AVT Specialist Meeting on Low Cost Composite Structures*.

Brandt, J., Geßler, A. and Filsinger, J., 2002. "New approaches in textile and impregnation technologies for the cost effective manufacturing of cfrp aerospace components". In *Proc. of 23rd Int. Congress of Aeronautical Sciences (ICAS2002), Toronto, Canada*. pp. 634–1.

Cazangi, H.R. and Martins, D., 2007. "Kinematic analysis of automotive gearbox mechanisms using davies' method". In *Proceedings 19th International Congress of Mechanical Engineering-COBEM. Brasılia-DF.*

Hartenberg, R. and Denavit, J., 1964. *Kinematic synthesis of linkages*. McGraw-Hill New York.

Hunt, K., 1978. *Kinematic geometry of mechanisms*. Oxford engineering science series. Clarendon Press.

Keilmann, R., 2002. "Blind stitch sewing mechanism". US Patent 6,470,814 B2.

Koissin, V., Ruopp, A., Lomov, S., Verpoest, I., Witzel, V. and Drechsler, K., 2006. "On-surface fibre-free zones and irregularity of piercing pattern in structurally stitched ncf preforms". *Advanced composites letters*, Vol. 15, No. 3, pp. 81–88.

Moll, A.R. and Schlondorff, R.G., 1988. "Surgical suturing machine". US Patent 4,747,358.

Nomoto, R., Takahashi, M. and Ebata, Y., 1984. "Suturing instrument for surgical operation". US Patent 4,484,580.

Reshetov, L., 1982. *Self-aligning mechanisms*. Mir Publishers, Moscou.

Rioux, R.F. and Sauvageau, D.J., 2004. "remotely-reloadable suturing". US Patent 2004/0236356 A1.

Saadi, E.K., Gastaldo, F., Dussin, L.H., Zago, A.J., Barbosa, G. and Moura, L., 2006. "Tratamento endovascular de aneurismas de aorta abdominal: experiência inicial e resultados a curto e médio prazo". *Brazilian Journal of Cardiovascular Surgery*, Vol. 21, No. 2, pp. 211–216.

Simoni, R., 2010. *Contribuições para a enumeração e para a análise de mecanismos e manipuladores paralelos*. Ph.D. thesis, Federal University of Santa Catarina.

Simoni, R., Carboni, A.P. and Martins, D., 2009. "Enumeration of kinematic chains and mechanisms". *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, Vol. 223, No. 4, pp. 1017–1024.

Simoni, R., Carboni, A., Simas, H. and Martins, D., 2011. "Enumeration of kinematic chains and mechanisms review".

Simoni, R. and Martins, D., 2007. "Criteria for structural synthesis and classification of mechanisms". In *19th International Congress of Mechanical Engineering - COBEM*.

Stokes, M.J., Albrecht, T.E., Ortiz, M.S., Zeiner, M.S., M., Z.A. and Shelton IV, F.F., 2007. "Method for instrument insertion through a body orifice". US Patent 2007/0239177 A1.

Thurm, T., 2004. "Application areas of one-side stitching technique". *Technische Textilien*, Vol. 47, No. 3, pp. 122–123.

Tischler, C., 1995. *Alternative Structures for Robot Hands*. Ph.D. thesis, University of Melbourne.

Tischler, C., Samuel, A. and Hunt, K., 2001. "Selecting multi-freedom multi-loop kinematic chains to suit a given task". *Mechanism and machine theory*, Vol. 36, No. 8, pp. 925–938.

Tsai, L., 2000. *Mechanism Design: Enumeration of Kinematic Structures According to Function*. Mechanical Engineering Series. Taylor & Francis.

Udakhe, J. and Basuk, M., 2011. "Sewing threads and their technical applications". *Fibre2fashion*.

Verdonck, P., 2008. *Advances in biomedical engineering*. Elsevier Science Limited.

Wittig, J., 2001. "Recent development in the robotic stitching technology for textile structural composites". In *International Sampe Technical Conference*. Vol. 33, pp. 540–550.

Yamamoto, T. and Chung, S.C., 2007. "Endoscopic suturing device". US Patent 7,175,636 B2.

Yan, H., 1999. *Creative Design of Mechanical Devices*. Springer.

Zhao, N., Rödel, H., Herzberg, C., Gao, S. and Krzywinski, S., 2009. "Stitched glass/pp composite. part i: Tensile and impact properties". *Composites Part A: Applied Science and Manufacturing*, Vol. 40, No. 5, pp. 635–643.

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