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AN INNOVATIVE METHODOLOGY FOR TOGGLE CLAMPING DEVICE DESIGN

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Abstract. *Clamping devices are elements that holds the workpiece during machine operation. Since the workpiece can have any shape there are many types of fixtures. Toggle clamps act as constraint instruments based on at least two equilibrium positions and are the focus of this study. The main objective of this paper is to show a innovative design process of toggle clamping devices based on the science of mechanisms. The steps of this methodology are summarized here. The main goal of this process is to build more innovative toggle clamps based on the current state of technology of these devices and on a classification that was also proposed by the authors. A new clamping device was developed to illustrate the application of this methodology.*

Keywords: *Toggle clamping device, Toggle clamp classification, Clamping mechanism, Mechanism design, Creative design*

1. INTRODUCTION

Fixtures, such as clamping devices, are tools that holds the workpiece during machine operation. There are many types of clamping devices, changing according to the application and workpiece shape. Boyes (1989) classifies the clamps in six basic types: strap, screw, wedge, cam, toggle and rack-and-pinion (see Fig. 1). Toggle clamps are commonly used in industry in cases which a fast fixture and release of the workpiece is desired.

Frequently, commercial toggle devices are based on the four-bar kinematic chain, such as Kipp K0660 (see Fig. 2a). Features are added with accessories mechanisms, but the device core remains a four-bar kinematic chain. A significant small amount of devices use mechanisms with a higher mobility or a higher number of independent loops that can lead to innovative designs with additional desirable features (Costa *et al.*, 2017). Examples of innovative designs are Bessey auto-adjust toggle clamps, which makes use of a more complex kinematic chain to add features such as fixing pressure adjustment and auto-adjustment to the workpiece size (see Fig. 2b).

While the design of simple clamps is well understood by many companies the development process of more complex equipments remains as industrial secret. There are methodologies for clamping design (Boyes, 1989; Pachbhai and Raut, 2014; Cecil, 2001; Hoffman, 2012; Joshi, 2010). Those methodologies are focused on the dimensional synthesis of existing toggle clamp, however, they are not focused on systematically searching for innovative toogle clamps.

Yan (1998) approaches the clamping design from a mechanism theory point of view. Yan's methodology seeks innovation through number synthesis of kinematic chains. number synthesis is a stage of mechanism design that presents a high level of abstraction but holds a great innovation potential. However, Yan's methodology is limited to kinematic chains with the same structural characteristics as mechanisms found in a survey. Besides, Yan focus on clamping devices and not on toggle clamping devices.

Innovative clamping devices with features such as auto-adjustment can be systematically designed using a methodology. However, no methodology for toggle clamping device that provides a structured approach for seeking innovation were found.

On this paper, we propose an innovative methodology for the design of toggle clamping devices based on mechanism theory. The methodology presented in this paper uses a novel clamping device classification (Costa *et al.*, 2017) to systematically search for innovative designs. A new toggle clamping device is designed to show how the methodology can be used.

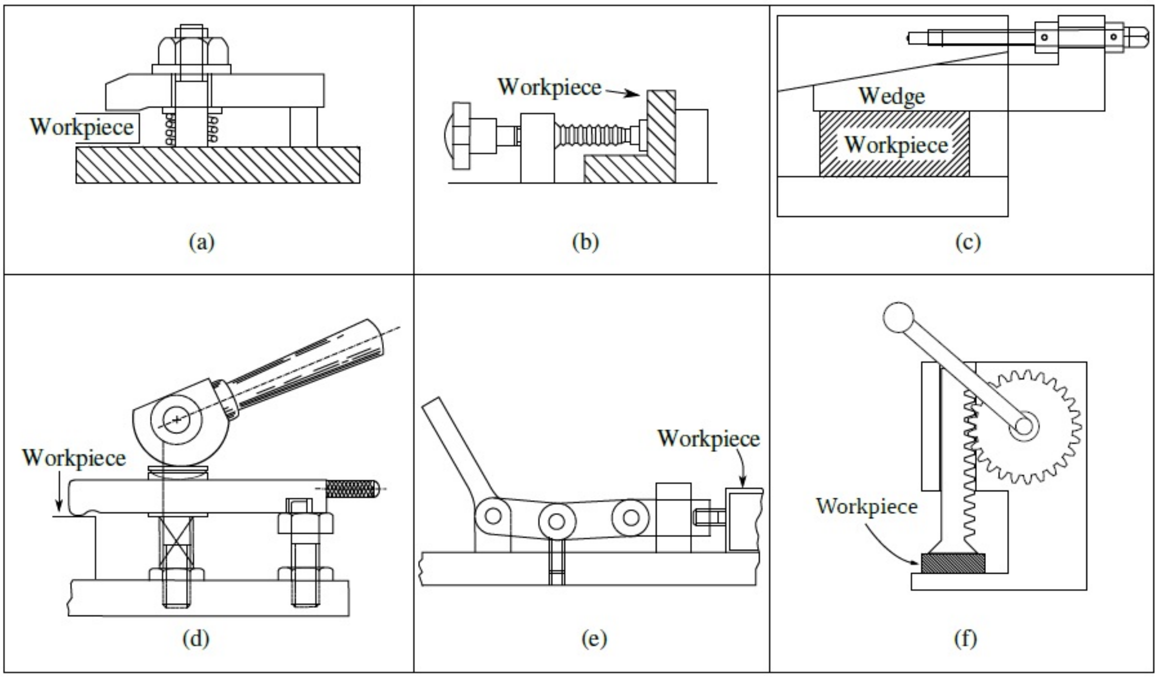
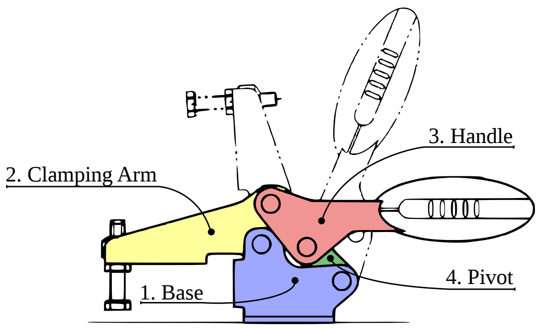
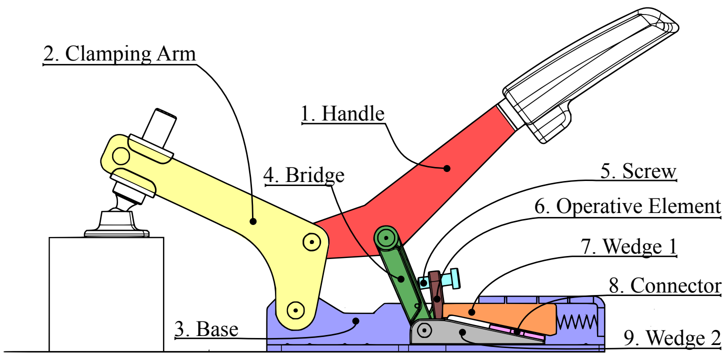


Figure 1. Types of clamping devices: (a) strap, (b) screw, (c) wedge, (d) cam, (e) toggle, (f) rack-and-pinion. Adapted from Boyes (1989).

Sec. 2 presents a review on key concepts of mechanism theory and a review on toggle clamping devices. Sec. 3 presents the proposed methodology. Sec. 4 shows the use of the proposed methodology to create a novel toggle clamping device with auto-adjust to workpiece size capability.



(a) Kipp K0660 clamp and its 4 main components.



(b) Bessey auto-adjust toggle clamp and its 9 main components.

Figure 2. Examples of commercial toggle clamp devices.

2. REVIEW

2.1 Review of mechanism theory

To understand the methodology of this work it is important to review some basic concepts about mechanism theory explained in this section.

The mobility *M* or number of degrees of freedom (DoF) of a kinematic chain is the number of independent parameters necessary to determine completely the disposition of a kinematic chain (Ionescu, 2003). The mobility of a kinematic chain is given by Kutzbach-Chebyshev-Gruebler equation (Eq. 1) (Simoni *et al.*, 2011).

$$M = \lambda(n - j - 1) + \sum_{i=1}^{j} f_i \qquad (1)$$

Where: λ is the number of degrees of freedom of the space in which a mechanism works (Tsai, 2001), *n* is the number of links, *j* is the number of joints and f_i are the degrees of relative motion permitted by joint *i*.

The number of independent loops in a kinematic chain is the number of loops that have at least one exclusive kinematic pair. A kinematic chain with ν independent loops follows the Eq. 2, called *Euler's equation* (Tsai, 2001).

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

Associating Eq. 1 and Eq. 2 produces the loop mobility criterion (Eq. 3) (Tsai, 2001).

$$M = j - \lambda\nu \tag{3}$$

For further information about mechanisms concepts see Tsai (2001); Ionescu (2003).

To create a new mechanism, Hartenberg and Denavit (1964) suggest to follow this three phases: number synthesis, type synthesis and dimensional synthesis.

Number synthesis starts from structural requirements (in general *M*, ν and λ) to define the number of links, kinematic pairs and which links are connected. So, many mechanisms that fills the structural requirements are created (Hartenberg and Denavit, 1964). Some mechanisms from number synthesis are selected to type synthesis according to some functional requirements specified by designer.

Type synthesis aims to determine types of each kinematic pair from mechanisms selected on number synthesis. First, the designer lists all possible kinematic pairs that can be used. Then, all possible types of kinematic pairs are distributed to selected mechanism kinematic pairs. Again, some solutions are selected to next phase (Hartenberg and Denavit, 1964).

Dimensional synthesis goal is to establish links dimensions (lengths and angles) to achieve the desired kinematic of the mechanism. In general, designers use a CAD software along with optimization routines in this phase. Static analysis, done for example through Davies Method (Cazangi *et al.*, 2008), aids the designer to determine objective functions used in optimization routines.

After dimensional synthesis it is time to make the prototype. Further adjustments can be done by returning to type or dimensional synthesis.

2.2 Review of clamping devices

This work first step was to define the current clamping devices state of the art in order to know how this technology was presented latterly. The research was made in three steps: academic, commercial and patent.

In general, academic research yielded definitions and old references. Yan (1998) was the only author founded who followed Mechanism Theory to develop new clamping devices. It is important to remember that Yan didn't work with toggle clamping devices.

The commercial research analyzed 444 devices from 5 companies. These companies usually classified the toggle clamping devices by the way the device secures the workpiece: hold-down, push-pull, latch and combination. The four-bar mechanism was used on the majority of kinematic chains found and just a few devices presented more complex kinematic chains. Commercial clamps also presented accessories such as clamping arm spindles, quick release levers and additional locks (Costa *et al.*, 2017).

Patent survey was made using *Google patents* and *espacenet* as search tools. It was analyzed 3198 patents related to clamping devices and 228 of them were selected. Like commercial clamping devices, most of the patents use the following kinematic chains: four-bar linkage, Watt, Stenphenson or a different inversion of the slider-crank mechanism Costa *et al.* (2017).

3. METHODOLOGY

The main goal of this paper is to provide tools that can aid designers to build more innovative toggle clamps. A design methodology is proposed on this paper, based on a toggle clamp classification previously presented (Costa *et al.*, 2017). This methodology was developed based on the works of Yan (1998) and Tsai (2001). The main aspect of this methodology is the use of Mechanism Theory to provide a structured approach for the creativity process. Thus, the clamping devices are here represented as planar kinematic chains and each of its features seen as mobilities.

A systematic method was followed to develop the classification and the design methodology. First of all, an extensive bibliography review was done to define the main authors and their contributions to the development of clamping devices. The second step was to define the current state of technology of clamping devices. Thus, an extensive survey in patent, academic and commercial areas were done. This survey was executed focused on products of the main companies in this market and the main intellectual property organizations in the world. More than three thousands patents and almost five hundred commercial devices were analyzed (Costa *et al.*, 2017).

A few kinematic features of these fixtures were evaluated. The devices were organized thought several kinematic categories such as degrees of freedom and connectivity. But since most of them were build based on the four-bar mechanism just the ones with more complex kinematic chains were deeply analyzed and helped to define the proposed classification.

Further, it was decided to classify the toggle clamping devices by its mobility (M) and number of independent loops (ν). Each class would be named with the code: M, the number of mobilities, and L, the number of independent loops. Thus, a device built based on a four-bar mechanism must belong to the $M1L1$ category. Together with an atlas of kinematic chains (Fig. 3), it is possible to establish which kinematic chains and configurations remains unexplored. Thus, an innovation map can be built based on the collected data. By choosing unexplored options in the innovation map it is possible to develop novel toggle clamping devices. The bibliography review, toggle clamp classification and the innovation map are presented by Costa *et al.* (2017).

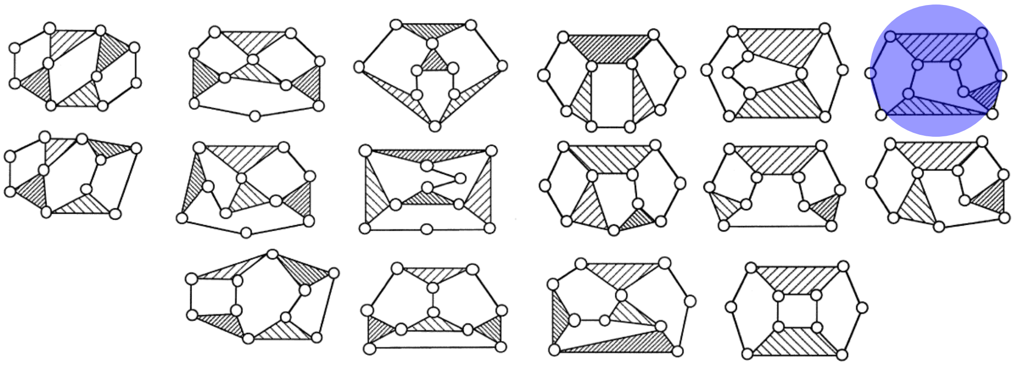


Figure 3. Atlas of planar $M1L3$ chains. The ones that are not highlighted remains unexplored. Adapted from Tsai (2000).

3.1 Design Methodology

The first step of any design methodology is to define the device's requisites and how each will be addressed by the current project. Some of this requisites, in clamping devices, are the number of contact points that touches the workpiece, the force applied to hold the object and the size adjustment capability. Analyzing as a kinematic chain, each of these features can be related to a mobility. Thus, the first step of this methodology must be to select the number of degrees of freedom of the mechanism.

The second step is the selection of the desired class based on the previously presented classification (Costa *et al.*, 2017). To do so, the designer will also have to define the number of independent loops. Kinematic chains with higher number of loops are more complex but will also present more innovation opportunities. After selecting the desired class, an atlas of kinematic chains can be used to verify which chains belongs to that class. One of the main innovation opportunities relies at this step, since its possible to choose kinematic chains that remains free from intellectual property issues.

The third step is the definition of the device's kinematic chain. There is no established methodology to define such chain, but a few aspects, such as the symmetry, complexity and variety can be held in consideration. It is important to pay attention to the occurrence of loops with mobility equals zero and the variety level of each independent loop.

At the fourth step, the definition of which joints will be locked as the clamping principle of this mechanism is required. To do so, it is important that the number of actuators in each independent loop remains smaller than the variety level. The locking principle must also be defined at this step. Most of the toggle clamps holds the objects based in kinematic singularity between two binary links, but other strategies such as a spring or a backstop can also be applied.

The fifth step is the definition of the fixed link of this mechanism. The way that the object will be held and the link that will act as the clamping arm needs to be defined as the sixth step. The most usual way is with a single rubber pin. The concept of controllability level must be applied to define the clamping arm.

The steps above mentioned defines the kinematic configurations of this device. Based on the size of the workpieces and the required mechanical proprieties a dimensional synthesis must be done. Most of the design issues must be addressed at this phase.

The current methodology can be summarized in the following steps:

1. Define the mobility of the mechanism;
2. Define which class belongs the kinematic chain of the mechanism;
3. Choose the mechanism's kinematic chain from an atlas if kinematic chains;
4. Define which pairs would be locked as the clamping principle;
5. Define the fixed link;
6. Define the link that will be used as the clamping arm;
7. Dimensional synthesis.

4. RESULTS AND DISCUSSION

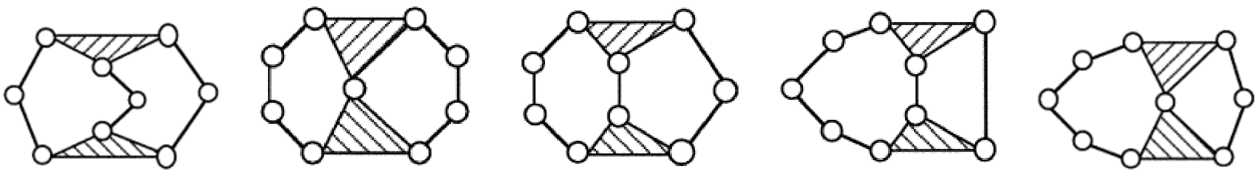
4.1 Design of a new toggle clamping device

In this section a new toggle clamping device is presented. Mechanism design methodologies based on enumeration techniques generate several results to be analyzed. Thus, several different mechanisms could be designed. As the focus of this section is to illustrate how the proposed methodology can be used to design innovative toggle clamping devices, in every decision making step only one of all possible options is explored.

Following the methodology proposed in Sec. 3, two desired features were considered for the clamping device: the toggle device must auto-adjust to different workpiece size; the toggle device must be able to compensate changes in the fixating pressure due to different workpiece sizes. Thus, the size adjustment and pressure adjustment added two degrees-of-freedom to the toggle clamping design. Together with the main toggle clamp mobility, a structural requirement for this toggle clamp is mobility three.

Analyzing the toggle clamps found in the state of the art review, it was noted only two devices that present mobility 3. Both devices are Bessey auto-adjusting toggle clamps, one device belongs to class $M3\nu1$ and the other to class $M3\nu4$. According to Simoni *et al.* (2011), there is only possible closed kinematic chain with mobility 3 and one independent loop, which is the kinematic chain used by Bessey. Regarding kinematic chains with mobility 3 and four independent loops, there is a total of 1962 possibilities and only one of them was used by Bessey. It is possible to design an innovative device using an already explored kinematic chain. To do so, different types of kinematic pairs could be assigned as well as different functions to the kinematic chain links. However, as in this example we focus on designing a novel toggle clamp, an unexplored planar closed kinematic chain with mobility 3 and 2 independent loops is chosen.

There are 5 possible closed planar kinematic chains with mobility 3 and 2 independent loops (Simoni *et al.*, 2011), as Fig. 4 exposes.



(a) (b) (c) (d) (e)

Figure 4. Closed planar kinematic chains with $M = 3$ and $\nu = 2$. Adapted from Tsai (2001).

The kinematic chain in Fig. 4a has variety 0, thus, any three kinematic pairs can be locked to yield a kinematic chain with mobility zero. The kinematic chains in Fig. 4b and 4c have variety 1 and the kinematic chains in Fig. 4d and 4e have variety 2. Thus, in the last four kinematic chains the selection of kinematic pairs to be locked must be done carefully to avoid possible overconstrains or links with undetermined position.

For didactic purposes, the kinematic chain in Fig. 4c is selected. Kinematic pairs and links are labeled as Fig. 5a. The next step is to identify the kinematic pairs that will be locked to reduce the mobility to zero. As the chain has variety 1, not all combinations of kinematic pairs are feasible to be locked. For instance, locking pairs b, c and f can result in overconstrain at the kinematic subchain in the right-hand side while one degree-of-freedom remains in the kinematic subchain at the left-hand side (see Fig. 5a).

There are several feasible combinations of locking pairs selection and fixed link selection, *i.e.*, the link in the mechanism that will be directly attached to the worktable. These different possible combinations generate different toggle clamps. For the purpose of example, let us consider the kinematic pairs b, g and i as locking pairs and link 1 as the link to be fixed.

The next step is to identify possible links for the clamping arm. To do so, first number of degrees-of-freedom that must affect the clamping arm position is established. In this example an auto-adjustment for workpiece size is desired. This adds one mobility to the kinematic chain which is used to adjust the clamping arm to the workpiece size. This extra mobility is taken out by restraining a kinematic pair position with a spring. Thus, the position of the clamping arm must be affected by the kinematic pair to be locked with such spring.

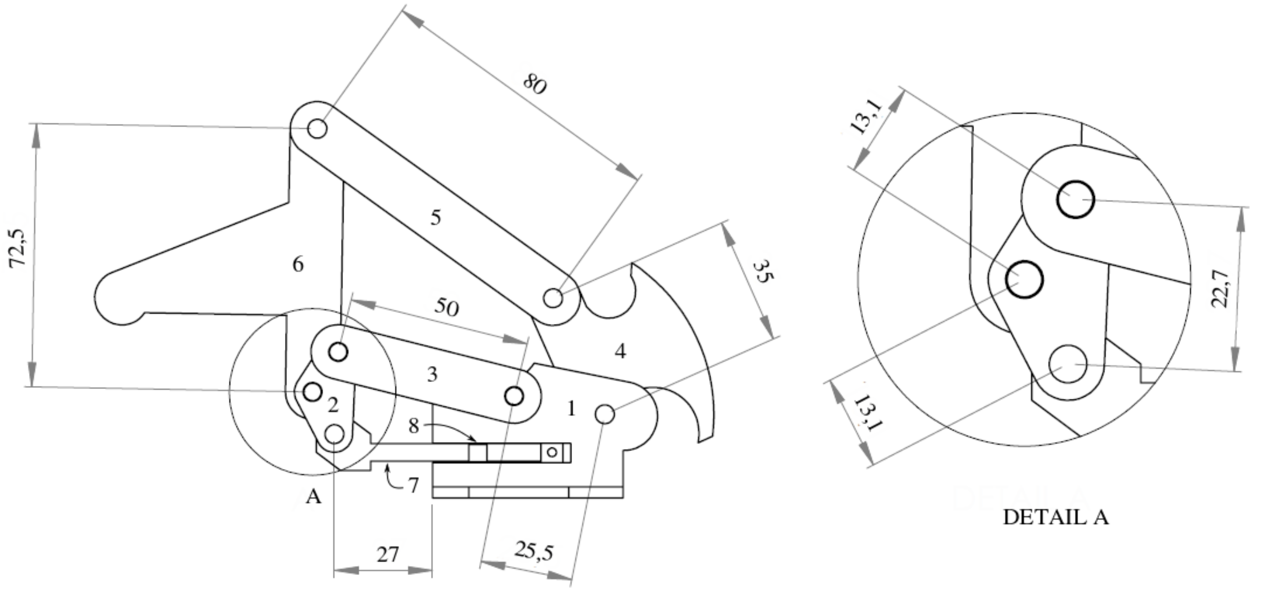
As in this example a fixing pressure adjustment is also desired, one mobility is added to the kinematic chain. This mobility must change the spring preload, affecting the fixing pressure of the clamping arm. Thus, by locking this kinematic pair in different positions different fixing pressures are achieve in the clamping arm.

Finally, the mobility of the toggle action must also affect the clamping arm position. So by operation the handle the clamping arm should get closer and hold the workpiece. Thus, all mobilities should affect the position of the clamping arm. Therefore, possible links for the clamping arm are those which are affect by all the kinematic pairs to be locked. To identify such links, the concept of actuated degree-of-control is used (Murai *et al.*, 2017). The links which position in relation to the fixed link 1 depends on all locked kinematic pairs b, g and i are links 4, 5 and 6. Choosing link 6 to be the clamping arm, the mechanism topology is presented in Fig. 5b.

(a) (b)

Figure 5. Topology for a new toggle clamping device with $M = 3$ and $\nu = 2$.

Finally, the mechanism dimensional synthesis is done. The toggle clamp designed in this section does not have a specific application and it aims to illustrate how to use the methodology. A proof-of-concept prototype was designed, the links dimensions are presented in Fig. 6. For specific application, an optimization routine could be used in the dimensional synthesis to achieve specific goals. For instance, the links dimensions could be determined to maximize the toggle clamp capability to auto-adjust to different workpiece size or to maximize the range of the fixing pressure.



(a)

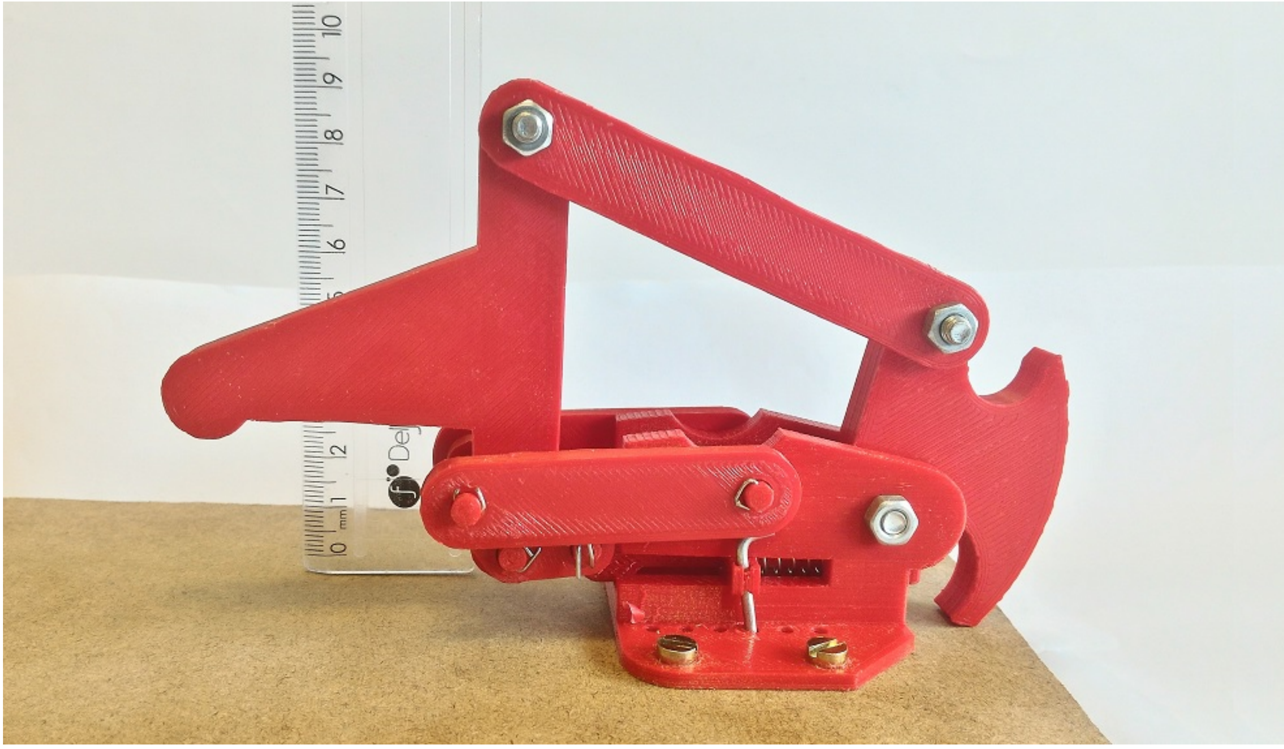
Figure 6. Mechanism dimensions of the proof-of-concept prototype. Dimensions in mm.

4.2 Manufacturing and testing

The prototype was 3D printed in ABS material using GTMax3D Core A1 3D printer. A compression spring with a constant stiffness of $455.55\ N/m$ was used in the kinematic pair *i*. This spring establishes the position of the kinematic pair *i*, which is responsible for the auto-adjustment to workpiece size. Figure 7 shows the prototype manufactured.

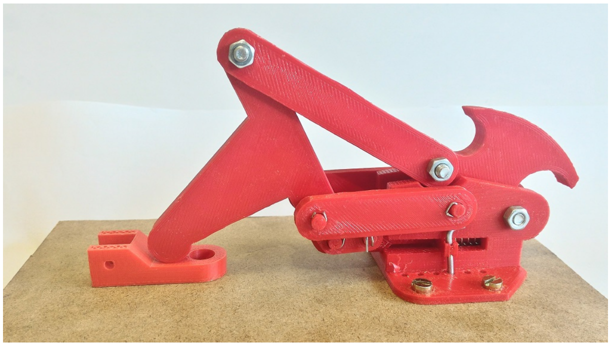
Four workpieces were tested with sizes 7 mm, 20 mm, 27 mm and 40 mm. In these set of experiments, the pressure fixing pressure adjustment was keep the same, *i.e.*, the relative displacement between links of the kinematic pair *b* was not changed. Regarding the capability to auto-adjust to different workpiece size, the toggle clamp manufactured was able to successfully fix all workpieces tested without requiring any adjustment. As expected, for larger workpieces the fixing pressure was higher than for smaller workpieces. For larger pieces the fixing pressure can be adjusted so that the toggle clamp can fix large workpiece with the desired fixing pressure. Figure 8 shows the toggle clamping device with different workpiece sizes and the same fixing pressure setup.

Regarding the fixing pressure adjustment, different fixing pressure setups were tested for the workpiece with a height of 20 mm. Initial testes showed that by changing the spring preload through kinematic pair *b* the force to dislodge the workpiece changed as expected. Thus, the adjustable fixing pressure feature was successfully implemented. Changing the spring for another one with a higher stiffness or a non-linear spring can achieve a larger range for the fixing pressure. Thus, when designing for an specific application, a static analysis is required to use a spring that fulfills the desired range

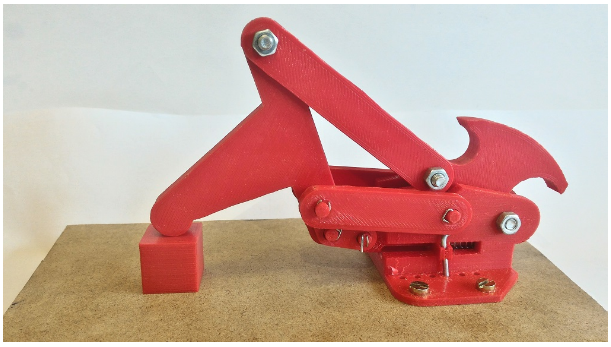


(a)

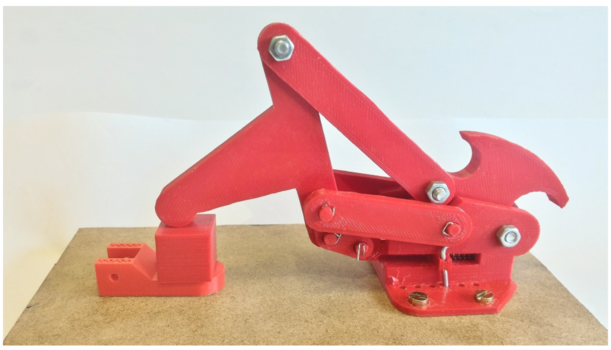
Figure 7. Proof-of-concept prototype, 3D printed in ABS material.



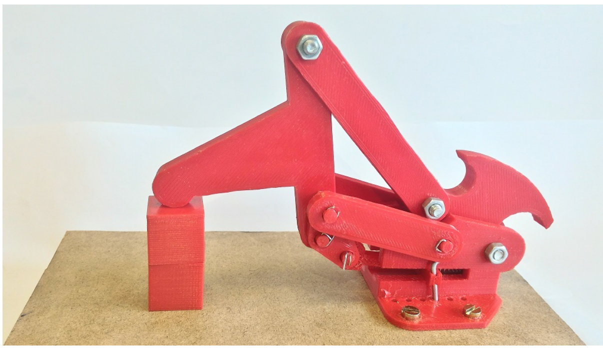
(a)



(b)



(c)



(d)

Figure 8. Prototype holding down workpieces of four different sizes. (a) 7 mm workpiece. (b) 20 mm workpiece. (c) 27 mm workpieces. (d) 40 mm workpieces.

of fixing pressure and workpiece sizes.

The research has shown that most of the clamping devices available at the market are based on the four-bar mechanism. Since this mechanism has only one DOF most of the devices built based on this chain cannot have additional features in the device core, such as self adjustment. These features have to be added by accessories, such as the clamping spindle. Because this kinematic chain is very simple, it was well explored by companies, making it hard to build innovative solutions based on this kinematic chain. Devices made using kinematic chains with more DOF could present more features without using accessories. The tools summarized at this paper are able to aid designers to build innovative devices with more DOF and functions. The case studies shown that some companies are already working with unconventional configurations and there is a huge number of kinematic chains that can be explored. New clamping device patents can be issued with the already used kinematic chains, however, there is a great innovation potential unexplored within other structural characteristics.

5. CONCLUSIONS

This paper presented a structured approach to generate innovative toggle clamping devices. A new methodology was proposed. The proposed methodology uses a state of the art review and a classification based on mechanism theory to identify unexplored kinematic chain and promising areas for development. To exemplify how the methodology can be used, a new toggle clamping device was designed according to the proposed methodology.

The new toggle clamp was designed and manufactured using additive manufacture. Initial tests showed the toggle clamp can successfully hold a workpiece, auto-adjust to different workpiece sizes and adjust the fixing pressure. Furthermore, the toggle clamp designed is an innovative design, validating the methodology capability of systematically search for innovation. The toggle clamping device designed in this paper is under patent process.

As it was exposed in Sec. 4, the methodology can be used to design other innovative, patentable toggle devices which the core kinematic chain presents embedded features, such as auto-adjustment to workpiece size. Therefore, this methodology contributions lies not only in the academic field but also in the industry.

As future works, the toggle clamp designed here can have its dimensional synthesis done to a specific application. Kinematic and static analysis will be done, changing the links dimension to optimize the toggle clamp performance. More experiments regarding the dependence among the fixing pressure adjustment, force to dislodge the workpiece and size of the workpiece are expected to be carried out.

6. ACKNOWLEDGEMENTS

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