# Review and Classification of Workpiece Toggle Clamping Devices

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**Abstract.** Clamping devices are the elements that hold the workpiece during the machine operation. Since the workpiece can have any shape, there are many types of clampings. The toggle clamps present at least two equilibrium positions and they are the focus of this study. An extensive survey in academic, patent and commercial areas was made to analyze the clamping device state of technology. The objective of this article is to propose a new classification using the results of patent and commercial survey and to develop a innovation map of these mechanisms. This new classification, together with an innovation map, can be used to aid designers when creating a new clamping device.

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

## 1 Introduction

During the manufacturing process, the workpiece is subject to many forces. A fixture is the tool that holds the workpiece during machining operation and it is often attached to the machine table [1]. Thus, a proper fixture design is related to the desired workpiece surface finish and dimensional accuracy, which determine the product quality. So, fixture devices are able to improve both the manufacture process quality and the final product quality [2].

Cecil [3] presents a clamping design methodology for automated fixture design. In Cecil's methodology, the designer can work on dimensional synthesis after selecting the type of clamping device. However, this approach does not consider number synthesis, being limited to a given kinematic chain. This limitation reduces the technological innovation potential for new clamping devices.

In this paper a survey on commercial devices and patents of toggle clamping devices is presented. Then we propose a new classification of clamping devices based on mechanism theory. The devices found in the survey are classified according to the proposed criterion and through the use of mechanisms atlas an innovation map is generated. This map can be used to aid the designer in the development of new mechanisms. Thus, innovation can be systematically searched through the use of an innovation map.


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## 2 Review on Clamping Devices

### 2.1 Academic Survey

There are many types of clamping devices, changing according to the application and workpiece shape. Boyes [4] classifies the clamps in six basic types: strap, screw, wedge, cam, toggle and rack-and-pinion. Figure 1 shows Boyes's classification.

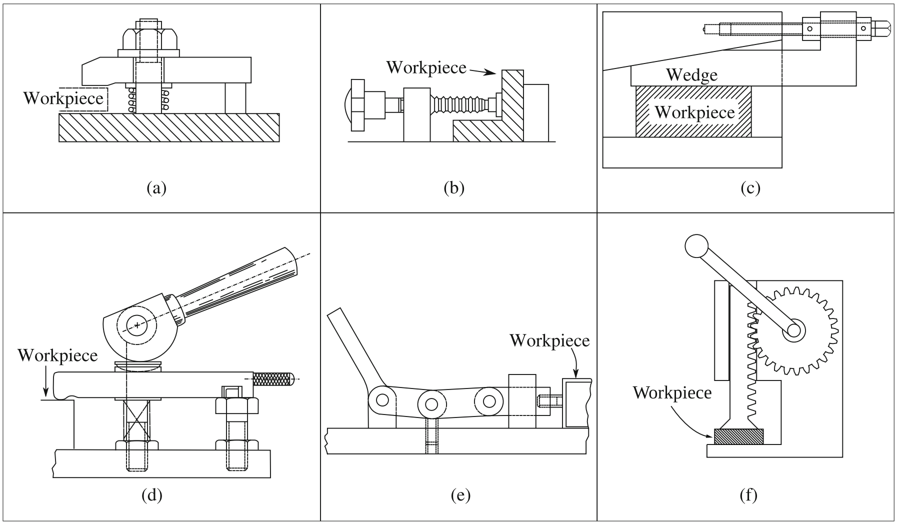



**Fig. 1.** Types of clamping devices: (a) strap, (b) screw, (c) wedge, (d) cam, (e) toggle, (f) rack-and-pinion. Adapted from [4].

The strap clamp is composed by a rectangular beam that contacts simultaneously the workpiece and a pivot point and is actuated by a component, such as a screw(Fig. 1a). The screw clamp acts based on the fastening of a screw attached to a fixed based (Fig. 1b). The wedge clamp is based on the motion of a inclined plane which gives the required clamping force (Fig. 1c). Cam clamps provides rapid and effective force using a cam shape piece to move the contact point and hold the workpiece (Fig. 1d). Toggle clamps are based on kinematic chains that have at least two equilibrium positions, providing heavy pressure and quick operation (Fig. 1e). The rack-and-pinion type uses the motion of a rack to transmit the clamping force (Fig. 1f) [4].

Boyes's classification aids designers in dimensional synthesis and provides a database to choose the best clamps to each application. Other authors propose similar classifications [1,2,5]. However, a classification based on working principle does not aid the designers in number synthesis stage, which is a stage with a high level of abstraction but holds a great innovation potential.

A mechanism design methodology is proposed by Yan [6] and applied to clamping devices. Yan's approach considers the clamping device in the closed position, *i.e.*, with the workpiece fixed. So, Yan searched for structures with negative mobility and three independent loops. Using enumerated techniques, 6 new design concepts were devised by Yan. Regarding Yan's methodology, it is constrained to explore kinematic chains with equal mobility and number of links and joints, reducing the search scope. However, promising and innovative solutions can exist outside those boundaries.

### 2.2 Commercial Clamping Devices

Seeking out to define the most significant features and characteristics of toggle clampings an extensive commercial research was made. In total 444 devices from five companies were analyzed. These devices are usually classified by the way the device secures the workpiece in four main types: hold-down, push-pull, latch and combination. In all the devices a rubber piece is used to create friction with the workpiece. The combination clamp touches the workpiece on two contact points and in more than one direction being able two hold the workpiece more precisely. These devices can be actuated by horizontal, vertical and angular handles.

The research has shown that most of the kinematic chains employed to build these devices are based in the four-bar mechanism. To build different types of clampings, companies employs several configurations for the handle, the clamping arm and the coupler. Just a few devices showed more complex kinematic chains. The major difference noticed among commercial clamps are accessories such as clamping arm spindles, quick release levers and additional locks.

### 2.3 Patent Survey

The patent survey was made using the search tools *Google patents* and *espacenet.* A total of 3198 patents related to clamping devices were analyzed, of which 228 were selected. A deep study extracted 41 representative patents of toggle clamps with different working principles.

This survey has shown that, similar to commercial clamping devices, most of the patents use the same working principle: four-bar linkage, Watt kinematic chain, Stephenson kinematic chain or a different inversion of the slider-crank mechanism. More details about the survey representative patents are exposed in Sect. 3.

## 3 Clamping Devices Classification Proposal

In this section a new classification for clamping devices is proposed, focusing on mechanism design. This classification, together with the innovation map exposed in Sect. 5, can be used to aid the designer when creating a new clamping device.

### 3.1 Considerations Regarding Accessories Features and Springs

Frequently, a clamping device is composed of a core mechanism responsible for the toggle locking action and accessories mechanisms which adds desirable features. Among the additional features found are adjustable fixing pressure, adjustable link size according to the workpiece size, different workpiece fixing posture, safe lock and quick release. These features are added to the core mechanism in peripheral mechanisms or by replacing a link with an adjustable link. See for instance Patent US4141543 [7], in which the possible embodiments include additional locking mechanisms using a ratchet or a pin in notch; a screw to adjust to different workpiece sizes; and push-pull or hold-down configuration. However, the core kinematic chain remains the same, a planar single-loop kinematic chain with mobility one.

Only the clamping device core is considered in this classification and accessory features are disregarded. This separates the device toggle locking action in the mechanism core from accessories features, making the design of new mechanisms easier. Also, accessories features can be added later to the new mechanism core as desired.

As the clamping device purpose is to fix a workpiece, the mechanism presents different degrees-of-freedom (DOF) from the opened to the closed position. In general, this is achieved by adding higher kinematic pairs to the kinematic chain, such as contact points, reducing the kinematic chain mobility. This is frequently associated with the singularity points at which the chain changes its configuration, such as elbow-up or elbow-down. The mechanisms are analyzed in the opened condition, so that their kinematic chains present a higher mobility.

Springs are often used in clamping devices to apply forces with a specific direction at a mechanism member. In some cases the spring function is to guarantee the kinematic pair closure, such as in patent US5527024A [8]. Springs with this function were disregarded to simplify both analysis and synthesis of new mechanism. When designing new clamping mechanisms with kinematic pairs that do not guarantee closure, the designer can add springs later to assure the pair closeness. In some cases the spring function is to reduce mobility by acting upon elements such that their positions are determined, as in patent GB2118896B [9]. In this patent, the spring length changes during the mechanism operation, allowing relative motion between the contacting elements. Thus, the spring was disregarded to obtain the mechanism mobility as it is during the device operation. Nevertheless, when designing new clamping devices with higher mobility, the designer can make use of springs to reduce the mechanism mobility on opened and closed position.

### 3.2 Clamping Device Classification Proposal

The clamp device classification is based on mechanism theory and the mechanisms are divided in three major classes according to their mobility:

Class M1: mechanisms in this class have mobility one. The core mechanisms in this class usually have less features. Accessories functions are done by adding peripheral components. Examples of mechanisms in this class are patents EP128 5731B1 [10], US5921535A [11], US2744552A [12], US5647102A [13] and US6845 975B2 [14]. The product KIPP K0660, which is analyzed in Sect. 4.1, also belongs to this class.

Class M2: mechanisms in this class have mobility two. The added mobility is used to self-adjust the clamping device for different workpiece sizes or to adjust the fixing pressure. Examples of mechanisms in this class are patents GB2480434B [15], US3281140A [16] and GB2118896B [9].

Class M3: mechanisms in this class have mobility three. The core mechanisms in this class are able to self-adjust for different workpiece sizes and they present fixing pressure adjustment. The core mechanism of Bessey auto-adjust toggle clamp, as seen at patent US20100148414A1 [17], presents mobility three and the two adjustment capabilities mentioned.

It is desirable to have a device with few components to reduce manufacture and maintenance costs. Using the graph representation of a kinematic chain [18], the quantity of links ($n$) and the quantity of single DOF pairs ($j$) in a mechanism are related with the number of independent loops ($\nu$) by the Euler's formula

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

The mechanisms can be further classified regarding their number of independent loops. Mechanisms with few links are desirable, however, in some cases loops are added to allow a different actuation. Patents US20060082040A1 [19], US5688014A [20] and US7178797B2 [21] show that an extra loop with a prismatic pair can be used to actuate the mechanism by pneumatic or hydraulic means.

Extra loops can also be used to devise a tandem holding arm, such as patent JP3671705B2 [22]; add a spring which can be used to adjust the fixing pressure, such as patent US2777347A [23]; and allow for a hold-down clamping device be used as a push-pull clamping device, such as Bessey STC-IHH15.

The core mechanism of clamping device AMF 6830 has one independent loop and mobility one, being classified as a M1L1. The mechanism from patent US68459 75B2 [14] presents two independent loops and mobility one, being classified as a M1L2. The mechanism from patent EP0163219B1 [24] has three independent loops and mobility one, belonging to class M1L3. Bessey presents two types of auto adjust toggle clamp. Patent US20100148414 A1 [17] shows the first type of Bessey auto adjust toggle clamp, here called Bessey 1. The mechanism from Bessey 1 has mobility three and one independent loop, belonging to class M3L1. Patent US20160184978A1 [25] shows the second type of Bessey auto adjust toggle clamp, here called Bessey 2. The mechanism from Bessey 2 has mobility three and four independent loops, thus, this mechanism is classified as M3L4. Analysis of Bessey 1 and 2 are exposed in Sects. 4.2 and 4.3, respectively.

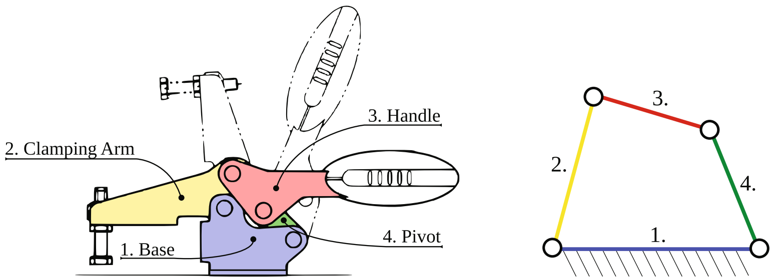
Section 5 shows how this classification can be used to identify unexplored areas, which can be useful to systematically pursue innovation. Besides its application for designing new mechanisms, a classification based on mechanism theory can be easily extended, differently than a classification based on application or working principle. As new mechanisms are developed, their core mechanisms can be analyzed and the corresponding class created.

## 4 Case Studies

After analyze almost 500 commercial clamping devices, the research has shown that, in a structural approach, the mechanisms available in the market are very similar and could be classified in a small number of classes. This paper summarizes theses devices into classes based on their mobility and number of independent loops. Three representative clamping device are analyzed as case studies, one for each of the following classes: M1L1, M3L1 and M3L4. As mentioned in Sect. 3, only the main kinematic chain of the device is analyzed. The motion of accessories attached to the equipment, such as clamping arm spindles, are not analyzed, since they can be added later and do not affect the core mechanism motion.

### 4.1 Class M1L1 - KIPP K0660

This class is composed by mechanisms with the following structural characteristics: $M = 1$ and $\nu = 1$. The most representative clamping device on this class is the KIPP K0660, a horizontal toggle clamp with flat foot and adjustable clamping spindle, which is shown in Fig. 2.




(a) Functional representation (b) Kinematic chain

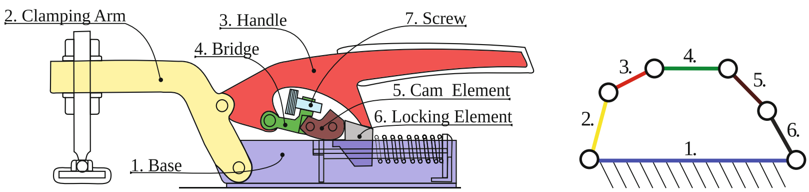
**Fig. 2.** KIPP K0660 clamping device

This device won the 2011 iF product design award and has an special feature called KIPPlock. This feature changes the device's kinematic chain, merging links 1 and 2 into a single body by locking the rotative joint between them with a pin. The K0660 has a wide range of models, with clamping forces varying from 250 N to 2800N. The manual force needed to close the device goes from 80 N to 280N.

This toggle clamp is composed by four major elements (Fig. 2a), all connected to each other by rotative joints. The core mechanism, responsible for the toggle action, is a four-bar linkage (Fig. 2b). The K0660's clamping principle is based on the singularity (Fig. 2a) created by the alignment of links 3 and 4, acting together with a stop surface on link 1.

### 4.2 Class M3L1 - Bessey 1

This class is composed by devices with a single loop and three degrees of freedom. Compared to the four-bar mechanism, the extra DOF can be used for additional features on the device. The representative device in this class is Bessey 1, the old generation of Bessey's auto-adjust toogle clamp. The three DOFs are used to execute the clamping action, the adjustment to various workpiece sizes and to change the holding force.



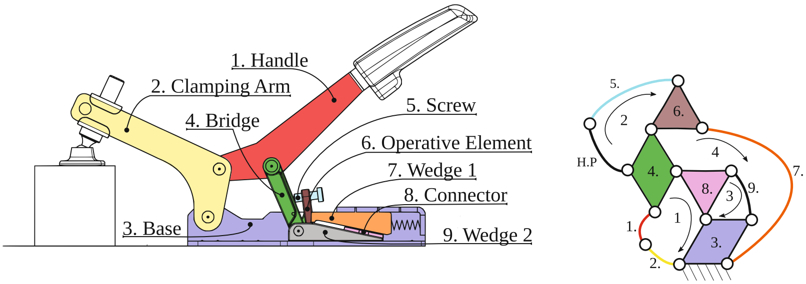

(a) Functional representation (b) Kinematic chain

**Fig. 3.** Bessey 1 - auto-adjust toggle clamp.

This device is divided into 6 main bodies (Fig. 3a). To achieve the holding position, with mobility 0, the device has to move through a certain number of singularity positions in the device's kinematic chain. The 3 DOFs need to be actuated only by the handle motion. The spring presented on the prismatic joint that connects the base and the pivot actuates one DOF and performs the equipment auto-adjustment capability. The second DOF is constrained from the device's kinematic chain when the cam shape of link 5 reaches the surface of link 4 (Fig. 3b), attaching those links together in one virtual link. The constant spring force and the physical connection between links 4 and 5 convert the device's kinematic chain into a single loop four bar mechanism. Thus, the last holding phase is achieved by the alignment of links 2 and the virtual link. The cam shape of link 5 also acts on the preload of the spring. The screw presented on link 5 defines which sector of the cam will affect the spring being able to change the spring preload, and thus, the clamping force.

### 4.3 Class M3L4 - Bessey 2

One of the most developed device found in the survey was the Bessey 2, the new generation of Bessey's auto-adjust toogle clamp. It has an auto-adjustment capability, being able to hold workpieces with various heights without any change on the adjustable clamping arm spindle. It also has a force adjustment feature,




(a) Functional representation (b) Kinematic chain

**Fig. 4.** Bessey 2 - auto-adjust toggle clamp.

allowing the user to change the clamping force by a screw. This device is composed by 9 major components and it is the most representative member of the class with the structural characteristics: M $= 3$ and $\nu = 4$. The four loops that compose the device's kinematic chain can be seen in the Fig. 4. Notice that, the kinematic pairs that connects the links 3, 8 and 9 are all prismatic pairs which axes are parallel to the mechanism plane. Thus, the subchain composed of links 3, 8 and 9 are on the third special 2-system, according to Hunt [26], and this loop presents mobility 1.

The mobility 0 position is achieved by the settling of the wedges together with the singularity by alignment of the bridge element and the handle. After reaching the singularity point, if the handle is moved further, the mechanical interference with the base stops the clamping arm motion.

Loop 1. Clamping motion: it is built based on a five link kinematic chain and it has two DOF. The main components are the handle and the clamping arm. It has four revolute joints and one prismatic joint. It is actuated by the handle motion and affected by the sliding of wedge 1. After wedge 1 position is settled, the clampling will hold the workpiece when the handle and the bridge align, reaching the singularity position.

Loop 2. Force adjustment: the force adjustment capability is based on a screw that interacts with the device by a higher pair. The screw pushes the bridge element and making the operative element interact with the wedge 2 by another higher pair. The amount of screw that is screwed in affects the spring preload.

Loops 3 and 4. Reconfigurability: as said before, the screw motion (9) moves the wedge 2 through the operative element. The position of wedge 2 with respect to the base affects the wedge 1 position, changing the amount of force used to hold the workpiece. The motion of wedge 1 relative to the base also allows the device to hold different sizes of workpieces, changing loop 1 singularity point.

Although this mechanism presents more components, it also has interesting features, such as auto-adjust regarding the workpiece size and fixing pressure adjustment. This features guarantee the same holding force while eliminating the need to manually adjust the clamping arm spindle for small variations on the workpiece size, reducing the setup time. In some cases the use of a more complex mechanism can be justified by achieving innovative designs with additional features.

## 5 Innovation Opportunities

Clamping devices are made to simplify the holding operation of workpieces. Devices which the core mechanism has only one DOF need manual adjustment to work with objects of various sizes. Usually this operation is done by adjusting a screw at the end of the clamping arm. The development of a clamping device with more than one DOF can allow several capabilities to the device, such as auto-adjustment.

As presented before, one of the main goals of the proposed classification is to guide the designer to new innovation opportunities in the designing of clamping devices. This strategy can lead to devices with more DOFs and more innovative devices. To build these new devices, various tools can be used as creativity sources, such as an atlas of generalized chains. For instance, the survey found only one of the 16 possible planar kinematic chains with $M = 1$ and $\nu = 3$. Figure 5 shows the remaining 15 unexplored options.

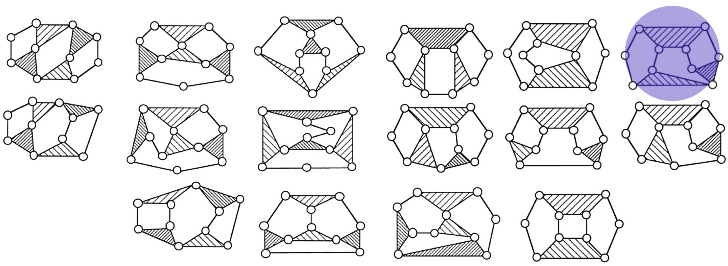


**Fig. 5.** Atlas of planar M1L3 chains. Adapted from [27].

Simoni et al. [28] present the quantity of possible kinematic chains for a given mobility and number of independent loops. Table 1 compares all possible kinematic chains with the configurations found in the commercial and patent surveys.

New clamping device patents can be issued with the already used kinematic chain, however, there is a great innovation potential unexplored within other structural characteristics. A more complex mechanism can be designed in exchange for additional features, which can improve the manufacturing process quality.

**Table 1.** Planar kinematic chains found on the survey.

| M | 1 | | | 2 | | | 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $\nu$ | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 4 |
| Possible | 1 | 2 | 16 | 1 | 3 | 35 | 1 | 5 | 74 | 1962 |
| Found | 1 | 2 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 |

## 6 Conclusions

This paper presented a survey on commercial devices and patents of toggle clamping mechanisms. A classification for these devices based on mechanism theory was proposed. Using the proposed criterion, it was noticed that the majority of commercial devices and patents, found in the survey, are variations of a few mechanisms. Most devices use four-bar mechanism, Watt kinematic chain, Stephenson kinematic chain or different inversions of the slider-crank mechanism.

However, a significant small amount of devices use mechanisms with a higher mobility or a higher number of independent loops. Two mechanisms with mobility three from Bessey were analyzed and it was noticed that they present auto-adjustment for different workpiece sizes and holding pressure adjustment. Thus, the use of kinematic chain with higher mobility can lead to innovative designs with additional desirable features.

The opportunities map show other kinematic chains that remain unexplored and can be used to pursue innovation. Therefore, by combining a state of the art survey, a mechanism based classification and a mechanism atlas it is possible to systematically search for innovation.

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