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Mechanical, Maritime and Materials Engineering (3mE)
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ME51010 Literature Report

A Classification and Systematic Literature Review of Fundamental Parallel Closing Mechanisms

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Abstract **— This paper presents a classification of fundamental parallel closing mechanisms, by means of a systematic literature review conducted as part of the DAPCA project - the development of a double articulated parallel clip applier. Nevertheless, this study does not limit itself to the medical field. The literature found is classified in six categories: compliant mechanisms, linkage mechanisms, mechanical meta materials, kinematic origami, tendon-driven mechanisms and industrial grippers. The search methodology is analysed and the classification is critically discussed.**

AIM: To provide a structured overview of the state-of-the-art parallel closing mechanisms, not limited to the medical field, and provide insight into a possible research gap or abundance of literature.

METHODS: A systematic literature review was conducted using various search engines amongst which Google Scholar, ScienceDirect, Scopus, PubMed, IEEE Xplore and Web of Science. The search queries are analysed using a tool specialised in finding the effectiveness of the search queries used.

RESULTS: During the identification phase, a total of nine search queries were used, resulting in 4040 articles found through database searching. After duplicate removal and applying exclusion criteria, a total of 3671 papers were left. These articles were screened based on the title and abstract. A total of 342 full-text articles were analysed for eligibility, 163 of which were included in the study.

CONCLUSION: A novel functional classification scheme is presented, based on a systematic literature review. The classification is showing an abundance of validated literature in compliant mechanisms. Although linkage mechanisms are considered to be part of the classical mechanical mechanisms, their documentation is less advanced than their compliant mechanism counterparts. Other categories were far less prominent or relatively unexplored, leaving them mostly in the conceptual design phase. Multiple input, multiple output topology optimisation can be a useful asset in designing parallel closing mechanisms.

Index Terms **— Parallel closing mechanism, parallel gripper, classification, systematic literature review.**

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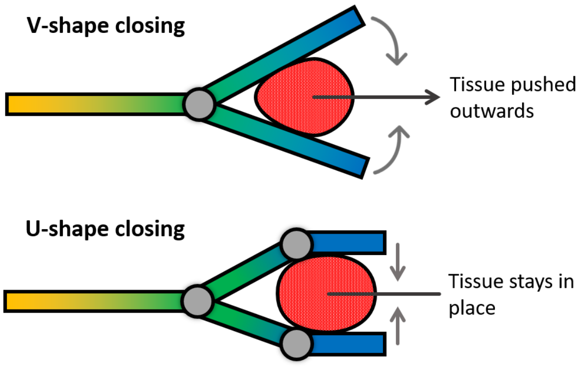
1 Introduction

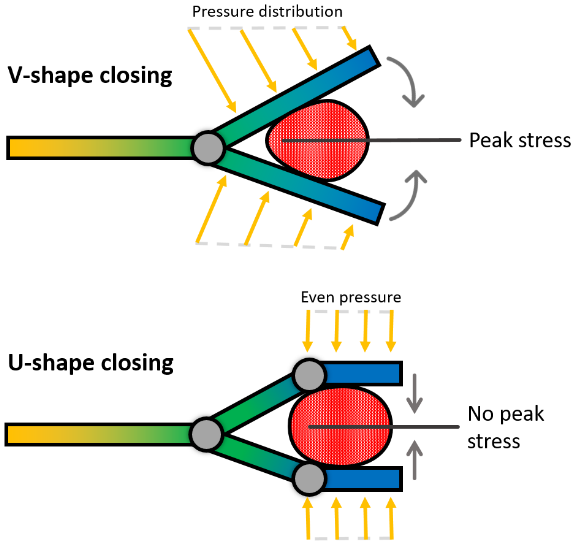
The upcoming DAPCA (Double Articulated Parallel Clip-Applier) project is in need of a novel design of a strong, foldable beak able to close in parallel. The state-of-the-art steerable clip appliers use v-shaped clips for ligation, i.e. to place clips around blood vessels or other tissue. One such mechanism is shown in Figure 1. This is a double articulated gripper, which has a 2-DOF movement of the end effector.

Figure 1: 2-DOF double articulated v-shaped clip applier.

This, however, causes the tissue that is being grabbed by the clip-applier to be pushed away. This problem will become even more prominent if the length of the beak is scaled down. The issue is illustrated schematically in Figure 2. V-shaped clip appliers also cause peak stresses in the end of the beak, near the hinge [123]. A parallel closing clip applier combined with u-shaped clips should eliminate these problems.



(a) Tissue being grabbed is pushed away with v-shaped closing.



(b) Peak stress present with v-shape closing.

Figure 2: Simplified overview of the difference between v-shape and u-shape clip appliers.

Some currently existing solutions make use of workarounds. They either bend the tip of the clip first by using a knee-joint [132] or they put the hinge of the beak far backwards ([67][75][143]). The latter causes the beak to close more parallel, but as a downside increases the length of the beak by increasing the amount of parallelism. Both examples are clearly shown in a video by Aesculap USA [2] (viewer discretion is advised). As the length of the beak increases, the mechanisms become unfit to be steerable. Therefore, a new design of the steerable clip applier is needed. Some v-shaped clip appliers also make use of a rough surface to decrease slipping by increasing the effective friction force [132], potentially damaging delicate tissue. In order to eliminate the peak stress in v-shaped gripping and allow for more parallelism, [156] proposed a clip that basically removed the end of the beak as shown in Figure 3. A group of doctors wrote a letter to the editor [45], to debunk the statement of the original author: “the closing pressure and angle of nonfenestrated clips may be a limiting factor" ... “as compared to fenestrated clips, which offer more parallel approximation of clip blades”. The doctors state that this cannot be considered true. These workarounds do not fully eliminate the problem. Also, these solutions require more space, which is undesirable.

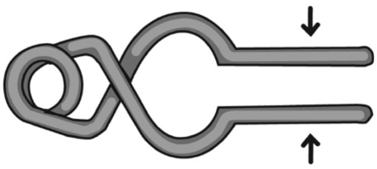


Figure 3: A 'parallel' clip with less peak stress than regular clips, proposed by [156].

Currently, an overview of parallel closing mechanisms is missing in literature. Therefore, this literature review will provide a classification of the state-of-the-art parallel closing mechanisms. The overview will indicate possible research gaps or abundance of literature. This paper will not only provide a structured overview of parallel closing mechanisms, but will have the added value of mapping what kind of literature terms are used for parallel closing mechanisms and a strategy for analysing search queries and reporting methods. The study will provide the foundation for my master's thesis, although this study is not limited to the medical field only. A separate conclusion will be written, to indicate which solutions might be interesting for my thesis. The challenge will not only be to come up with a novel parallel closing clip-applier mechanism, but also to make the beak strong enough, especially if a compliant mechanism is desired. This improves the overall cleanliness of the design and opens up new possibilities. Think of alternative manufacturing methods for prototyping, like 3D-printing. That, in its turn, will allow the part to be easy and cheap to manufacture. This could potentially help third world countries which are in need of such a device.

Compliant mechanisms have already established a history of uses and applications. According to Howell [68], traditionally, when designers are in need of a moving machine, they commonly use stiff and rigid parts connected with hinges. Howell [68] drew the conclusion that in nature, we see entirely different ideas. These ‘moving machines’ are very flexible instead of stiff and are made out of one part instead of multiple ones.

According to Howell [68], the advantages of compliant mechanisms include but are not limited to high precision, low cost, and ease of miniaturisation. Compliant solutions are therefore the preferred solution to the DAPCA project. However, the compliance comes at the cost of increased fatigue failure and more complicated designs due to nonlinearities.

This research will investigate what the state-of-the-art parallel closing mechanisms are and how these can be classified. The title of the paper is in coherence with this research question, namely: “A Classification and Systematic Literature Review of Fundamental Parallel Closing Mechanisms", which can be explained as follows. A 2D-classification scheme is made from state-of-the-art parallel closing mechanisms. This classification is also interpreted and analysed, which makes the research a literature review. A systematic approach is taken in order to find relevant literature and make the research reproducible. Parallel closing mechanisms are mechanisms of which the jaws open and close in parallel with respect to each other. The research is restricted to fundamental parallel closing mechanisms, because the author is only interested in the working principles of the mechanism itself. This excludes for example industrial grippers, as they often only show the resulting motion and outside of the gripper, while the internals are classified, being a so called 'black box'.

The structure of this literature review is in accordance with the layout of a qualified systematic review by Buia et al. [16], which is peer reviewed and approved and will be used as a template to follow for this research. Also the 'How to Write a Literature Review Paper?' document presented by Wee and Banister [148] is consulted.

2 Method

This section will describe the search method used during this research, by first showing the resulting PRISMA flow diagram and then describing the keywords and search engines used during this research.

The bibliography style for this paper is chosen to be numeric-APA, which follows an APA-style bibliography, with numeric citations instead. This means that the bibliography is ordered alphabetically, but no author-year citations are used. At first this had to be done because the classification scheme shown in Figure 8 would literally become too big. Using a mix between author-year style in the body of the document and numeric style in the classification scheme was not desired, as it would only become confusing. Secondly, the research of Himmelstein [66] on the advantages and disadvantages of numeric versus author-year citation style concluded that numeric citation styles are more applicable for modern literature. As of 2018, PubMed central reported 86% of the published articles were using the numeric citation style as well. Giving up on in-text author credit by name and insight in the publication years, now only accessible in the bibliography.

2.1 PRISMA flow diagram

The flow diagram in Figure 4 is based upon the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method [110]. The PRISMA Statement consists of a 27-item checklist and a four-phase flow diagram. According to PRISMA, the flow diagram depicts the flow of information through the different phases of a systematic review. It maps out the number of records identified through database searching and additional identified records, included and excluded items, and the reasons for exclusions. The latter will be explained outside the flow diagram, to keep the figure structured. The PRISMA statement is followed to help improve the reporting of this systematic literature review and meta-analysis. Originally, only a Word template was available for the flow diagram, so a LaTeX template is proposed in this paper, which can be used from now on. The code is available on Github (PRISMA). An online PRISMA flow diagram generator can be found as well, but these figures are not customizable or available in LaTeX.

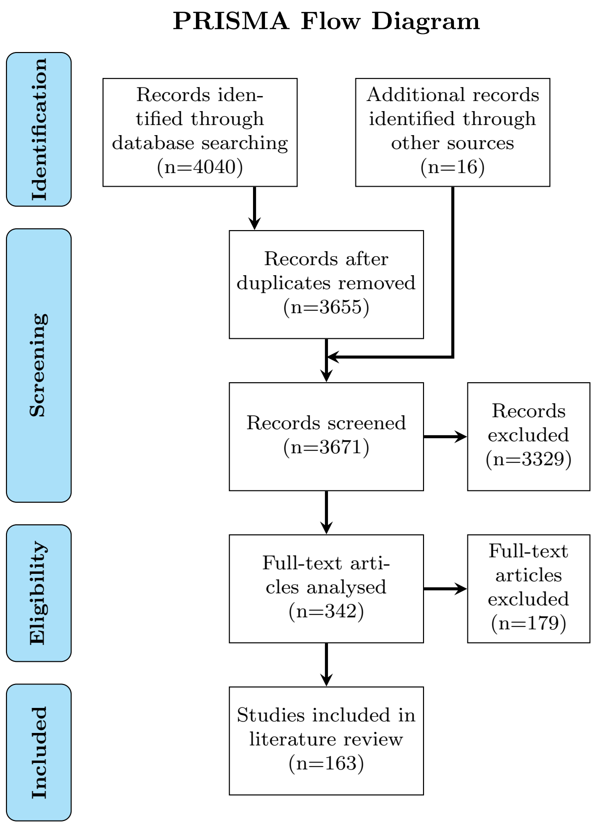


Figure 4: PRISMA flow diagram for systematic literature review (based on [110]).

2.1.1 Identification phase

Before including and excluding research studies, the relevant literature has to be searched first. The identification phase includes the search through databases, which results in records found. These records contain all found literature through database searching. The records still have to be screened and the eligibility criteria have to be applied, so the amount of relevant articles is yet to be determined and could be smaller than the amount of records during the identification phase. The database search through all databases, which are explained in subsection 2.3, resulted in a total of 4040 records, shown in the top left of Figure 4.

Additional records were also found through other sources. These records are found during the so called secondary search procedures. These procedures include, but are not limited to:

- Checking if authors published more articles (on the same research topic).
- Based on relevant patents, look for new patents with the same classification code (e.g.A61B2017/00292 - Surgical instruments, devices or methods, e.g. tourniquets for minimally invasive surgery mounted on or guided by flexible, e.g. catheter-like, means).
- Consulting the Mendeley Reference Manager's suggested literature page. This page recommends relevant research based on the references that you saved to your library.
- Consulting other classification papers. For example, the paper of Gallego Sanchez and Herder [50], from Delft University of Technology.

2.1.2 Screening phase

The screening phase consists of two parts. The first part is to remove duplicates and the second part is the actual screening of the articles themselves. During the screening phase, potential relevant found literature is selected from the total amount of found literature through database searching in the identification phase.

Google Search Query Uniqueness Identifier Program

During the first part of the screening phase, an open source tool was developed which extracts all search results from a particular search query and calculates the amount of unique results with respect to other search queries and the amount of double results within the same search query. The amount of double results are caused by Google itself, due to the way papers are referred to. A different citation method will result in a new record shown in Google. It seems as if Google also shows a different result of each paper if the result contains a pdf, html page, book or updated patent number.

It looks like if two papers cite a particular book in different ways, each citation will be included separately in your search result. In a particular case, the exact same article was included five times in one search query, see Figure 5. These are basically all places where Google has found the paper, resulting in unnecessary search results and possibly double work. It would be a nice addition from Google's side to filter out these results and give only one result for each paper. Possibly even note down if there were multiple instances of the same paper found and where they were found.

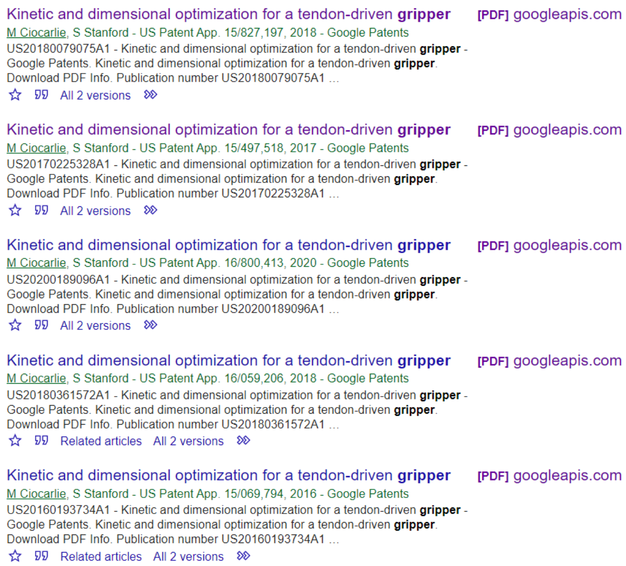


Figure 5: An example of multiple instances of the same paper in search query 3 (Table 1) of Google Scholar.

These metrics help with making a search plan of a literature review strategy, before conducting the study. One could easily leave out search queries which are not contributing to the overall information span, i.e. a low amount of unique papers with respect to your other search queries. This means all of the results in that particular search query are already included in your other search queries. This can save a lot of time for the researcher due to only reviewing search queries with relatively high number of unique results. The tool is called the Google Search Query Uniqueness Identifier Program (GSQUIP). The tool is written in Python and is publicly available on GitHub (GSQUIP). A video demonstrating the usage of the tool is also shown on YouTube.

Duplicate literature was removed by using a duplicate remover tool from Mendeley Reference Manager Desktop. There were a total of 385 duplicates found, which resulted in 3655 unique papers which were ready to be screened. These are indicated in the screening phase of Figure 4.

Screening

The second part of the screening phase was the actual screening of literature itself. For this, the title was interpreted for relevancy to the topic and the abstract was read to make sure the literature was potentially relevant for this study. Also, the articles were skimmed through, by downloading the article as PDF and previewing the contents. The figures were looked at too, as they often say more than words can do. Figure 4 shows that a total of 3671 records were screened, of which 3329 were excluded. The exclusion criteria are discussed in subsection 2.5.

2.1.3 Eligibility phase

During the eligibility phase, all records are scanned first. In particular, the inclusion criteria as discussed in subsection 2.4 are searched within the article. According to Figure 4 total of 342 full-text articles were analysed for eligibility using this method. 179 of which were excluded.

2.1.4 Included phase

Articles which were still present after the identification, screening and eligibility phases, were included in this literature review. These articles are relevant to the literature review and meet all inclusion and exclusion criteria which were set. They are either part of the classification scheme presented in this paper or other parts of the study. As shown in the fourth phase of Figure 4, this phase included a total of 163 articles. All of these references were categorised and saved using the Mendeley Reference Manager and web importer plugin.

2.2 Keywords

The keywords used during the initialisation phase are documented in this section. These keywords were included in the search queries of all the databases used. A distinction is made between main keywords and secondary keywords. At last, the database 'relevancy ranking' is critically discussed, as this plays an important factor in which research was and wasn't included in this literature review. Each search engine has it's own type of relevancy ranking.

2.2.1 Main search queries

Table 1 lists the search queries used during this literature review. These keywords are used along all databases. A total of nine search queries, indexed in the first column, together with the corresponding search phrases with keywords are shown. These are exact search phrases, so quotation marks were used, e.g. for the first search query "parallel closing mechanism". The use of the asterisk wildcard was not possible when using phrases, so the singular form is used in most of the cases. Exact phrases were used for the most relevant keywords, to limit the amount of papers found.

The third column includes additional inclusion keywords. These were added using boolean operators. These are specific to the type of search engine used, but in the case of Google scholar this is the 'AND' operator. Multiple keywords are added using the 'OR' operator. Next to the inclusion keywords, the exclusion keywords are shown, as well as additional filters. For example, filter by date and language restrictions. If there are too many search results, only the papers published in the last two decades (from 2000 onward) are analysed. Also, when the amount of search results was too big, patents and citations were excluded. According to Google Scholar, a total of 3468 search results were obtained and scanned. However, Google Scholar uses an estimate for the amount of papers. 3350 were found instead, which is calculated using the tool that was developed for the purpose of finding the effectiveness of each search term.

2.2.2 Secondary search queries

During the search process, and in particular scanning through relevant literature, secondary search keywords were obtained as one became more familiar in the field of parallel closing mechanisms. These were also limited to the English language. These secondary search keywords included, but were not limited to:

- Origami inspired mechanism.
- Parallel jaw gripper.
- Equal force gripper.
- Meta-material.
- Wide stroke gripper.
- Open-close gripper.
- Multiple-input-multiple-output (MIMO) devices.
- Tendon mechanism.

These keywords were used in addition to the ones shown in Table 1. However, not as extensive documented because it is expected that the resulting papers found through searching with these secondary keywords, are also included in the main search with original keywords. They are mainly listed because it is handy to gain some insight in the keywords used by other authors in the field. Parallel closing mechanisms are an extensive field of research with lots of different terms describing basically the same principle. The table will help to get familiar with terms that are used the most.

2.2.3 Relevancy ranking literature

Search results for Google scholar were ordered according to Google's "relevant" sorting order. According to Nelson [113], search engines used to be seen as "query tools", providing only results which fit the search query exactly. If one searches for 'A AND B', all papers with A and B in it, are relevant. There is no ambiguity. This is what is called the 'user understandable definition' of relevancy, as in: "did the engine correctly execute my query?". However, there has been a shift from this user understandable definition, to a more hard-core definition. This definition aims at answering the question: "does the document actually answer my question or solve my problem?". This kind of remains a grey area, as it is not clear to the user what the search engine finds "relevant". It's not clear anymore what the search engine is basing it's results on, which was very clear in the early days of the user understandable definition. Also, different search engines could be using different definitions for their score-functions of relevancy, therefore ranking the same paper differently, which could lead to a biased outcome of the study.

A reasonable attempt was made in order to perform this study as unbiased as possible, by using incognito web browers or clearing the cache memory before each search on Google, as Google is known to base the search results on location and previous search terms [59]. Sorting by date was also used, as according to *Find out more - Google Scholar (EN) - LibGuides at Utrecht University* [46] the relevancy sorting is unbalanced. Older papers have an advantage over newer papers, as google's relevancy sorting also prioritises papers with a high number of citations (assuming papers will get cited more over time).

2.3 Search engines

A wide variety of search engines were used to perform this literature review, to make sure that no specific area is left out. Of course within the limited time span that was available. The different search engines used to perform the study are listed in Table 2. Due to time constraints, some search engines might be missing from this list. It has to be noted, that Google Scholar also included journals like ScienceDirect, Springer, IEEE Xplore and Google Patents, making it the most suitable search engine for this literature review. There could be others as well, but these were at least encountered during this research.

The vast variety in search engines used, from multidisciplinary to subject-specific, made sure there were lots of different research types included as well. The research types included in this study are at least:

- Books.
- Conferences.
- Journals.
- Magazines.

[1]Patents and citations are excluded from this search query, due to the large amount of search results.

Table 1: Search strategy keywords and results with inclusion and exclusion criteria. GS = Google Scholar, WSQ = Web Search Query

WSQ	Exact phrase	And	Year	NOT	Language	Results	% Unique	% Double	Selected
1	Parallel closing mechanism			"non-parallel"	GB, NL, DE, FR	4	0	50	2
2	Parallel clamping	mechanism OR gripper OR device	2010-20	"non-parallel"	GB, NL, DE, FR	238	97	15	8
3	Parallel closing	mechanism OR gripper OR device	2000-20	"non-parallel"	GB, NL, DE, FR	191	94	18	16
4	Parallel gripper		2010-20	"non-parallel", "statically balanced", "motion platform", "constant-force", "parallel manipulator"	GB, NL, DE, FR	1140[1]	94	1	17
5	Parallel grasping	mechanism OR device OR gripper		"non-parallel"	GB, NL, DE, FR	186	79	4	31
6	Parallel linkage	mechanism OR device OR gripper	2010-20	"non-parallel", "statically balanced", "motion platform", "constant-force", "parallel manipulator"	GB, NL, DE, FR	811[1]	99	3	1
7	Clip applier	parallel	2010-20	"non-parallel"	GB, NL, DE, FR	413	100	8	2
8	Compliant gripper	parallel	2010-20	"non-parallel", "statically balanced", "motion platform", "constant-force", "parallel manipulator"	GB, NL, DE, FR	321	86	0	9
9	Origami gripper	parallel		"non-parallel"	GB, NL, DE, FR	46	96	4	4
Total						3350	⌀ 83	⌀ 12	90

Table 2: Different types of search engines used in this literature review.

Search engine name	Type of database
PubMed	Subject-specific: medical
ScienceDirect	Multidisciplinary
Web of Science	Multidisciplinary
Scopus	Multidisciplinary
IEEE Xplore	Multidisciplinary
Google Scholar	Multidisciplinary

- Patents.
- Standards.
- Technical reports.
- Theses.
- Websites.

Both peer-reviewed and relevant non-peer reviewed research was included.

2.4 Inclusion criteria

In addition to the keywords used and the inclusion criteria already stated in column four of Table 1, other inclusion criteria are used to reduce the amount of papers found and to retrieve the most relevant literature to the topic of this study.

For example, the mechanism has to be applicable to laparoscopic instruments. Because this is too subject specific for the purpose of this literature review, this criteria is masked under the general criteria that the mechanism should be able to be down-scaled to the order of ten millimetres. In case the mechanism is too small instead, the mechanism should be able to be upscaled to this order of magnitude.

The mechanism also has to be applicable to laparoscopic instruments. This means that the mechanism should be easily cleanable. For the same reason as mentioned above, for the purpose of this standalone literature review, the general criteria to achieve this, is that the mechanism should preferably contain no more parts than current existing clip appliers. Non-complex geometries are desirable, due to assembly and manufacturing considerations.

2.5 Exclusion criteria

Table 1 already shows some exclusion criteria in columns four and six, but there are some additional criteria which are explained below.

Papers which include non-parallel closing mechanisms are directly rejected. So are papers which mainly focus on the control aspect of parallel grippers and don't go in depth into the design of the mechanism itself. Papers about motion platforms, Steward platforms - umbrella term: parallel platforms - are not desired either.

First of all, the design or prototype of the research supporting it, may not be too bulky to start with. This is kind of a vague term, but the design has to be able to be scales to the order of millimetres, as already discussed in the inclusion criteria.

Also, the designs have to have, or are able to achieve a high amplification ratio. This is the ratio between the input motion and output motion of the gripper:

$$R_a = \frac{d_{output}}{d_{input}} \tag{1}$$

Where d_{input} and d_{output} are the in- and output displacements of the gripper, respectively. Designs that are too bulky and don't have a high amplification ratio, will be excluded from the study.

In analogy to the amplification factor mentioned above, grippers that have a notable low grasp-to-body ratio will be excluded as well. The grasp-to-body ratio is defined as follows:

$$R_{bg} = \frac{w_{grasp}}{w_{closed}} \tag{2}$$

Where w_{grasp} is the maximum grasp width and w_{closed} the width of the end effector when the gripper is closed (i.e. the closed body width).

A high grasp-to-body ration in conjunction with a high actuation-to-body ratio is not desired. Therefore, grippers with a high actuation-to-body ratio are excluded as well. The actuation-to-body ratio is defined as:

$$R_{ab} = \frac{d_{input}}{w} \tag{3}$$

Where d_{input} is defined as the input displacement and w the total width of the gripper.

Industrial grippers are often capable of achieving high output displacement, but don't meet the criteria of the actuation-to-body ratio.

3 Results

Table 1 gives the amount of search results per search query for Google Scholar. The last column also shows how many of these results were selected for this literature study.

While this is interesting information in itself, it does not give much insight into the effectiveness of the used search queries in order to form a search strategy. The uniqueness of each search query is an important metric in order to validate the effectiveness metric for the search query in question. Therefore, the custom made program is used as a tool to calculate the amount of double papers and the amount of unique papers. The percentage of unique papers is the amount of which the papers in the search query are unique with respect to all other papers, found by all search queries.

To gain insight in the amount of papers found per year, Figure 6 is made. This is valuable information in itself, as it shows the general trend of the amount of papers published over time in the research field. Also, this figure helps to compensate for the lack of publishing year information, which is visible using author-year style and has been lost in the numeric citation style. The general trend from 2000 to 2020 is a quadratic function, with correlation coefficient (R^2) of 0.78. This trend line is calculated using polynomial regression (the method of least squares), directly in LaTeX. There is some literature found before 2000, but these papers are in the far minority and are more spread out over time. This information isn't included in the figure, to keep the figure compact and the state-of-the-art more recent/relevant. All papers before the year 2000, were describing linkage mechanisms.

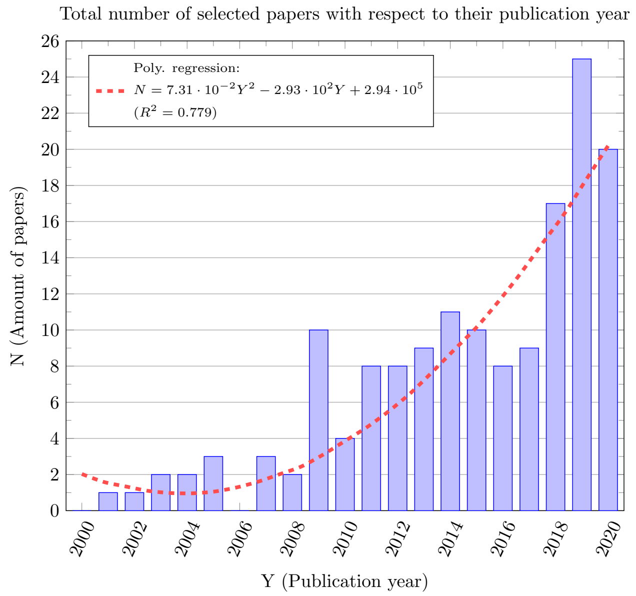


Figure 6: Total amount of selected papers related to parallel closing grippers, using the search strategy as presented in Table 1 and Table 4. 2nd order polynomial regression is shown to indicate a trend line of exponential growth with R-squared of 0.779.

During this research, there was a notable difference in the design stage of each paper found. Therefore, insight in the phase of the papers is desirable. This is done via a functional classification diagram. The main results are presented in subsection 3.1.

3.1 State-of-the-art classification

The relevant literature research included in this study is, in addition to Figure 6, divided into top level categories. The papers found during the literature search phase, are classified into categories based upon the found literature. These categories are divided further into a top level classification of each category, derived from the suggestions made by previous literature. The literature suggesting these additional categories, are shown as references behind the main classification categories as follows:

- Compliant mechanisms [18].
- Linkage mechanisms [127].
- Mechanical meta materials [139].
- Kinematic origami [14].
- Tendon-driven mechanisms [119].
- Industrial grippers [34][23].

These categories are presented in the form of a 3D-histogram. subsection 3.3 will elaborate more on these categories. The 3D-histogram in Figure 7 is made up of the amount of papers per year, per category. It shows the amount of papers found per category and proposes a standard template for displaying such information. The code to make Figure 7 can be found on Github (3D-Histogram). The code can be used as template for other research, in particular systematic literature classifications, to display the amount of papers found per category in a structured manner. The template is fully customisable.

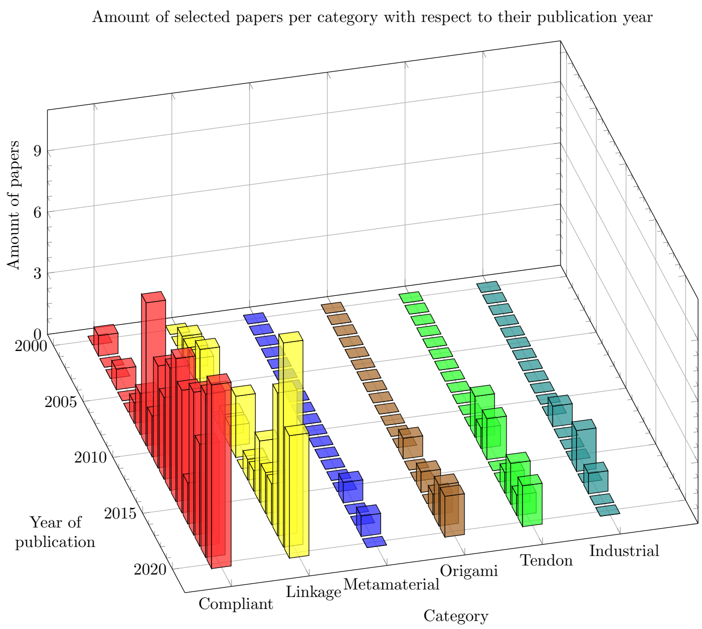


Figure 7: 3D-histogram showing the amount of selected papers per category as specified in the classification of Figure 8, over time. It has to be noted that some search queries, as shown in Table 1, were selected from year 2010 onward, so the figure is most accurate from that point in time. Also, industrial grippers were not part of the scope of this paper, so no effort has been made to search for these type of grippers specifically.

The results of the found literature is classified into top level categories. Each paper is then assigned into a specific design phase. These phases are following the general design iteration cycle of engineering. The resulting classification is shown in Figure 8. The figure shows all relevant literature concerning parallel closing mechanisms. The figure is made interactively, which means one can easily jump from a certain entry in a a specific category and design phase, to the bibliography and back. Each bibliography entry is therefore equipped with a back citation link. Each category has it's own colour, in accordance with the previous figures and each level of sub category becomes lighter. The level of depth of the sub categories can then be easily identified. The citation nodes in the large grey box on the right contain the actual references to the research in question. The LaTeX code for this classification can be found on GitHub (classification). Using this code as a template in future research, will result in a structured overview which is easy for the reader to comprehend.

3.2 Design phases

The design phases of Figure 8, are based upon any iterative engineering design cycle. There are many variations currently existing, but they all follow the roughly same incremental iterative method. For this literature review, four common phases are chosen:

1. Conceptual design phase.
2. Detailed design phase.
3. Verification phase.
4. Validation phase.

These phases are visualised in Figure 9. Each of these phases will briefly be explained in the next sections.

Although these design phases are assumed to be known to engineers, they can be derived for literature as well. The classification paper by Gallego Sanchez and Herder [50] makes a clear distinction between the conceptual and detailed design phase and the article by Speer [135] elaborates on the validation phase.

3.2.1 Conceptual design phase

The conceptual design phase is an early phase of the design process. The problem statement and relevance of literature is stated. Overall requirements are formulated and early concept designs are presented. Also, the current state-of-the-art is discussed.

3.2.2 Detailed design phase

During the detailed design phase the design of the product is presented. Usually in the form of computer-aided design (CAD) and working drawings. This does not have to be the final design yet, as designing is an iterative process. Specifications and dimensions of the design are shown and the analytical open or closed loop (inverse) kinematics have been presented. Thought has been put into the assembly method of the product. Also, possible manufacturing methods have been considered.

3.2.3 Verification phase

The verification phase includes a first prototype as a proof of concept. To verify the design and working prin-

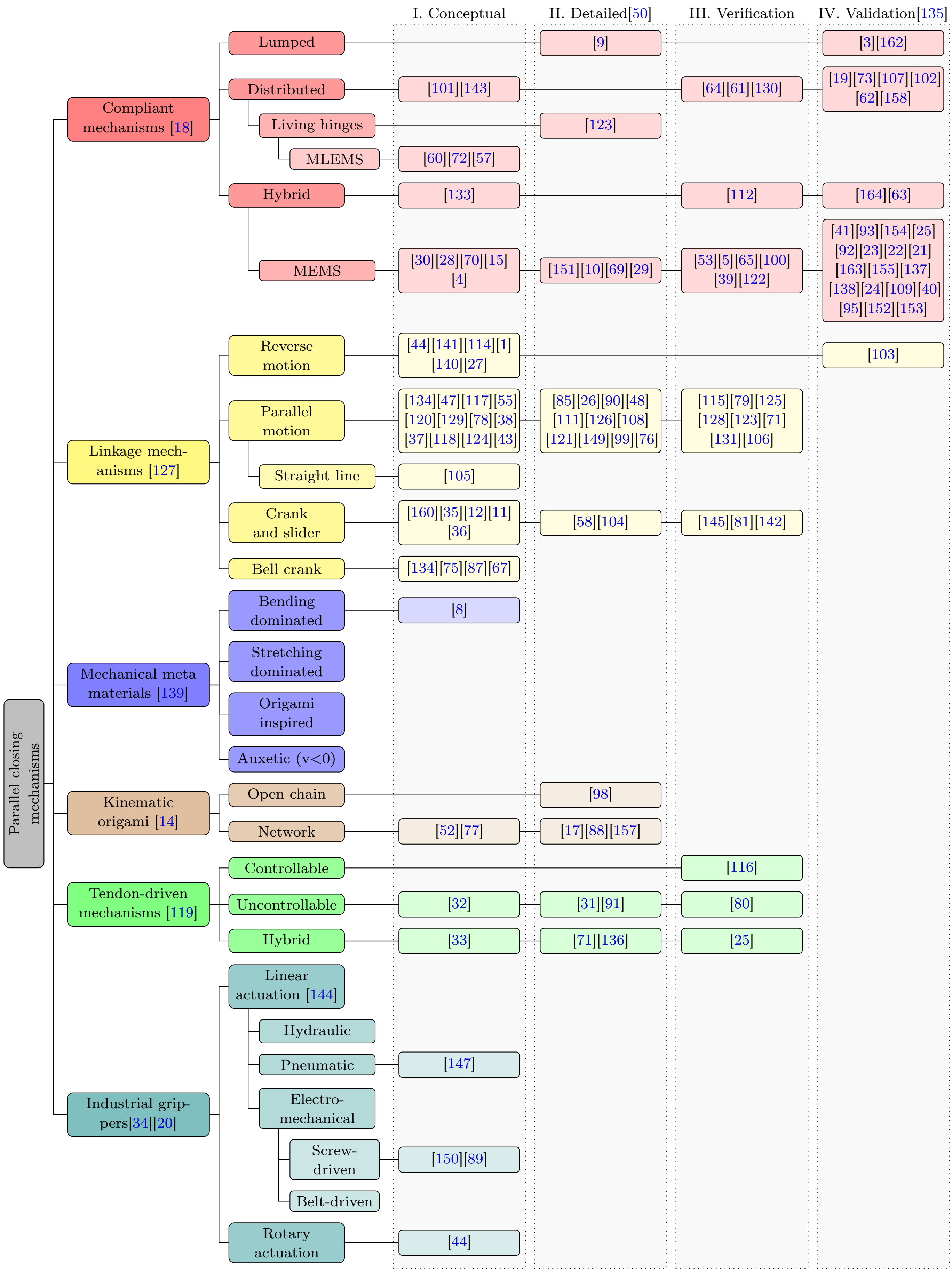


Figure 8: Proposed top level classification of parallel closing mechanisms. Selected papers were ordered in accordance with the phase of research they were in. Tree diagram layout was made with the help of the Tex Stackexchange community.

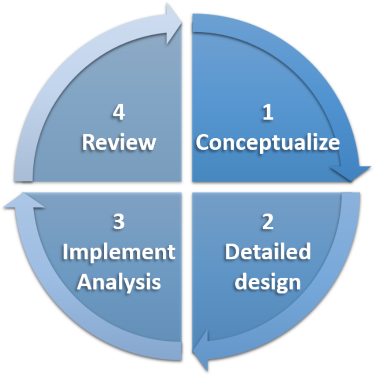


Figure 9: A general simplified iterative engineering design cycle.

ciple of the product. Finite element analysis (FEA) is also part of this phase. This in order to verify if the detailed design will work as expected. These two subjects are put into one phase, as a lot of papers tend to differentiate whether they prioritise making a prototype or using FEA to verify the design.

3.2.4 Validation phase

One of the last steps in the engineering design phase, is the validation of the product. This is usually done by making a (scaled) working product and performing experiments to validate if the product is performing as desired. The results are extensively reviewed.

3.3 Categories

The categories presented earlier have sub categories as well, which will be explained later on. The classification as shown in Figure 8, is a 2D-classification, with the different categories represented by colour on the vertical axis and the design phases, as explained earlier, on the horizontal axis.

3.3.1 Compliant mechanisms

There are three types of compliant mechanisms. A classification of compliant mechanisms was made by [18]. The mechanisms were divided according to the distribution pattern of compliance in the mechanism. The following three sub categories are distinguished:

- Lumped
- Distributed
    - Living hinges
        - MLEMs
- Hybrid

The first category is the lumped compliant mechanism, the second one distributed compliant mechanisms and the last one is a combination of the two, namely the hybrid compliant mechanisms. These mechanisms will be explained next.

Lumped
Lumped compliant mechanisms are compliant mechanisms which mostly depend on local deformations to obtain the desired motion and stiffness of the structure. A benefit is that these types of mechanism are more predictable, but large deformations are not possible because plastic deformations in the hinges could occur. Analytically, they are easier to model as well, using for example the pseudo-rigid-body model (PRBM) method. Lumped hinges have a central point of rotation, due to it's localised deformation. An example of a lumped compliant mechanism is shown in Figure 10.

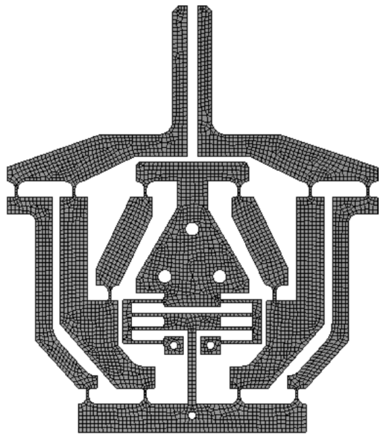


Figure 10: A meshed lumped compliant mechanism, which was analysed and developed by [162].

Distributed
Distributed compliant mechanisms are the opposite of lumped compliant mechanisms. While lumped compliance makes use of the rigidity of the interconnected bodies, distributed compliance makes use of it's flexibility instead. No local deformations are present anymore, but flexures are used to restrict the degrees of freedom instead of hinges. Figure 11 illustrates the deformation of these kinds of mechanisms. Distributed flexures don't have a fixed point of rotation, opposed to lumped hinges. Moreover, the point of rotation actually changes when the flexure is bent.

Living hinges Living hinges are a subcategory of distributed compliance. They simulate the hinge of lumped compliance, but with distributed deformations instead. These mechanisms share the advantages of both types of mechanisms, but also share the same downsides. These hinges are shown in Figure 12.

MLEMs Multi-layer Lamina Emergend Mechanisms (MLEMs) use living hinges in combination with multiple layers or sheets, which emerge from a thin surface. MLEMs are therefore a subcategory of Living

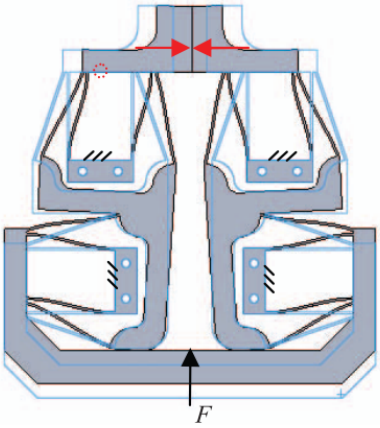


Figure 11: Distributed compliant mechanism shown in initial and deformed state [64].

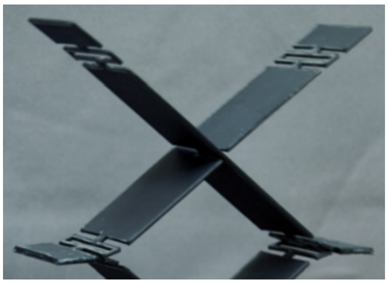


Figure 12: A typical use case for living hinges: the scissor type elevated mechanism [57].

hinges. These mechanisms usually are very flat, but take up a lot of space on a 2D-plane. This is because of the living hinges. One such mechanism is shown in Figure 13. This mechanism is opening and closing in parallel.

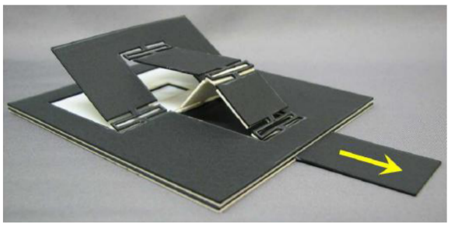


Figure 13: A MLEM mechanism converting an in-plane motion to parallel opening, using a four bar linkage mechanism in combination with living hinges [72].

The working principle of the MLEM mechanism is shown as an animation in Figure 14.

Hybrid
A hybrid compliant mechanisms is a mechanism which shows characteristics of both lumped and distributed compliance. These mechanisms generally can achieve higher deformations than lumped compliance, but slightly less than fully distributed compliant mechanisms. The added lumped compliance can increase stiffness. Figure 15 shows such a hybrid mechanism, with both hinges and flexures indicated.

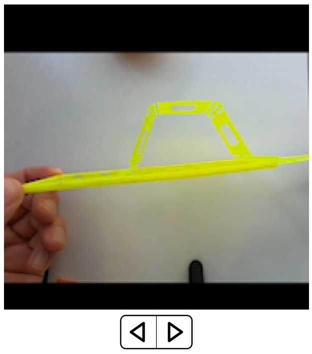


Figure 14: An animated figure, illustrating the kinematic movement of the MLEM mechanism. The prototype consists of three laminar layers and is 3D printed using PLA.

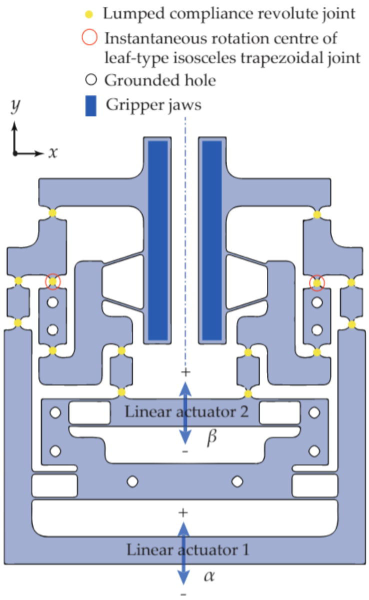


Figure 15: A hybrid compliant mechanism indicating local and distributed deformation patterns [112].

To emphasize the difference between lumped and distributed compliance, a comparison can be seen in Figure 16. This is an animated series of .png files which can be played using PDF viewers such as Adobe Acrobat Reader DC, by pressing start. These parts were FDM 3D-printed on a Creality Ender 3 Pro. For locally deformed hinges, another material like TPU had to be used. Regular PLA would not last long and break after a few times of bending. Using distributed compliance however, PLA can be used because the local deformations are smaller and the total deformation is spread accross the length of the flexures.

MEMS mechanisms Since there is a lot of information to be found on the specific subject of microelectromechanical systems (MEMS), a separate category for parallel closing mechanisms of this type is made. These mechanisms are by default very small, but they are still relevant since they can be up-scaled in size.

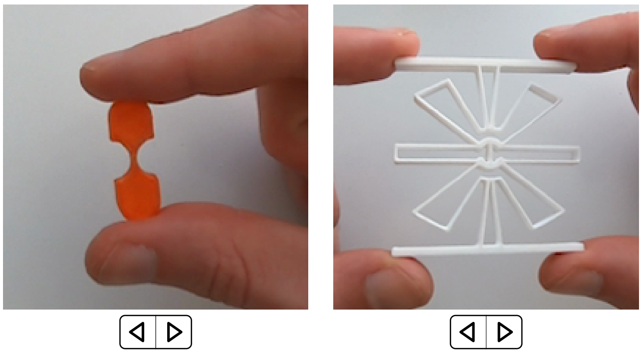


Figure 16: An animated figure, clearly showing the difference between local and distributed deformation. Both examples are 3D printed hinge joints.

Most of these papers concern themselves with the amplification ratio - defined as the amplification between the input and output motion of the system. However, since space is not really an issue on such scale, they are relatively bulky compared to their gripper tip displacement. The grasp-to-body ratio might be something to consider. Papers claiming to have a "large displacement gripper" usually have a low grasp-to-body ratio, which might be misleading readers. Figure 17 shows an example of a typical MEMS mechanism.

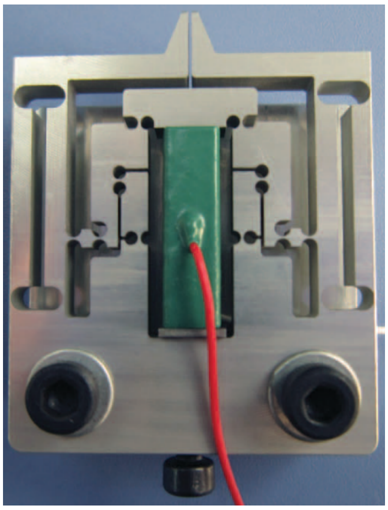


Figure 17: A typical MEMS system fabricated using WEDM. The mechanism is driven by a piezoelectric actuator in the middle [137].

3.3.2 Linkage mechanisms

Linkages allow forces and motion to be transmitted through a rigid connection. To get the forces to where they are needed, the least amount of play in the hinges and no elastic bending of the linkages are desired. According to Ryan [127], there are four main types of linkage mechanisms:

- Parallel motion
- Reverse motion
- Crank and slider
- Bell crank

These sub categories will be discussed below. A video showing the working principles of these mechanisms, can be seen here.

Parallel motion

The parallel motion mechanism is also known as the four bar linkage, but other configurations of this mechanism are existent too. The working principle of these parallelogram type mechanisms is as follows. Define two points of rotation on the two smaller, parallel moving rods. As a large linkage at the top of the mechanism moves to the left, smaller linkages at the bottom move to the right, with the two parallel rods rotating around the pivot points. Figure 18 gives an example of this mechanism, as it is a gripper with four bar linkages stacked on top of each other.

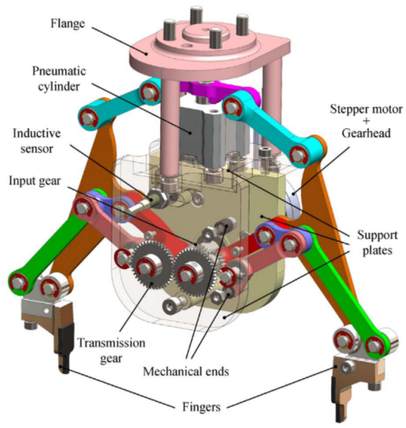


Figure 18: Linkage mechanism with a stacked four bar linkage [125].

Straight line Straight line mechanisms are a type of parallel mechanism, where linkages in a certain configuration can produce a point to move along a straight line. In contrast to the classical four bar linkage, the rods of these kinds of mechanisms don't have to be parallel to each other. And example of such mechanism is shown in Figure 19.

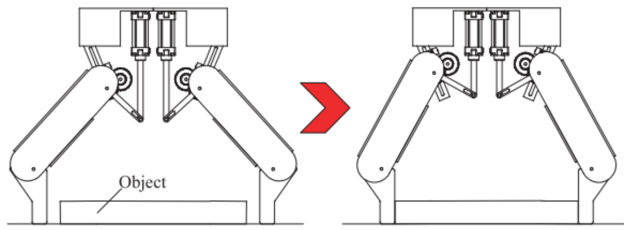


Figure 19: Application of a straight line mechanism with linear trajectory [105].

Reverse motion

The reverse motion linkage mechanism makes use of rotation of two rods around a pivot point. Two types of reverse motion linkages were found.

The first one is the scissor-type reverse motion linkage mechanism. An example is shown in Figure 20. A rotation of two linkages around a pivot point, can create a linear motion.

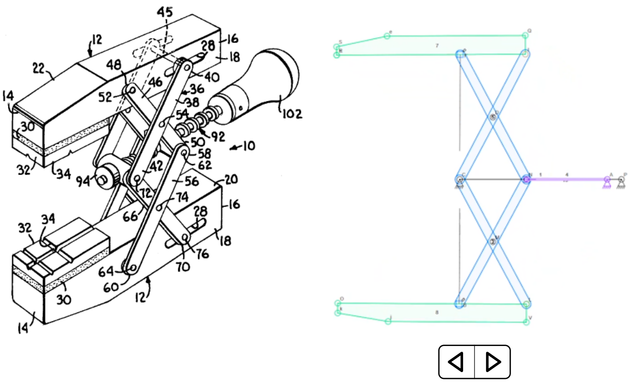


Figure 20: Scissor-type reverse motion linkage mechanism [140].

The second type is the elevator mechanism, for lack of a better naming convention. These types of mechanisms are often used for opening and closing elevator doors. The top and bottom linkage move in opposite direction, by means of a rotation of the connecting linkage around the center of rotation. An example of such a mechanism is shown in Figure 21.

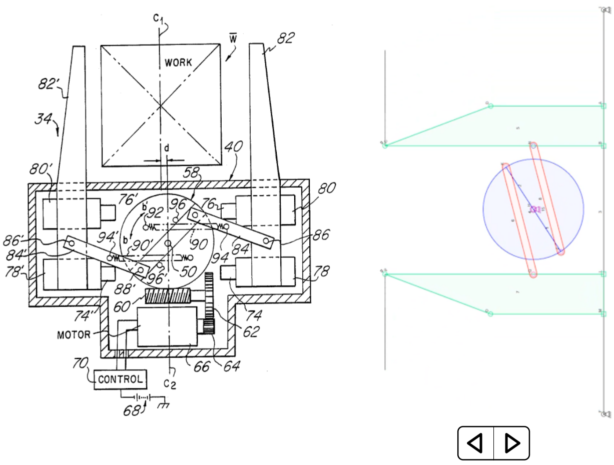


Figure 21: Elevator-type reverse motion linkage mechanism [114].

Crank and slider

A crank and slider linkage mechanisms converts a rotation into a translation. A rod moves back and forth in a slider mechanism, while a centralised pivot point fixated the mechanism to the base. This mechanism somewhat resembles the straight line mechanism, but needs one less linkage. An example of a crank slider mechanism is shown in Figure 22. The animated figure has been made with an existing tool. This linkage mechanism designer and simulator tool is made for the purpose of visualising bar linkage mechanisms.

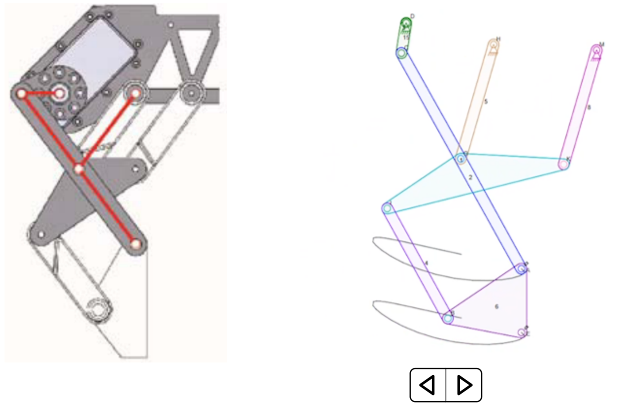


Figure 22: CAD model of a crank and slider mechanism [142]. The linkage mechanism is animated in the right figure, for clarity of the motion.

Bell crank

Some linkages can change the direction of a movement, the size of a force, or make things move in a particular way. More often than not, they do several of these things at once. Bell cranks are used to change the direction of motion through 90 degrees. Allowing horizontal movement to be converted into vertical movement. This is useful for taking motion around a corner. The bell crank mechanism also works in the opposite way of motion. A well known example is the bicycle brake. A more application-oriented example for this literature review, is shown in Figure 23. Although this is not a truly parallel closing mechanism, it can easily be made parallel by using a four bar linkage.

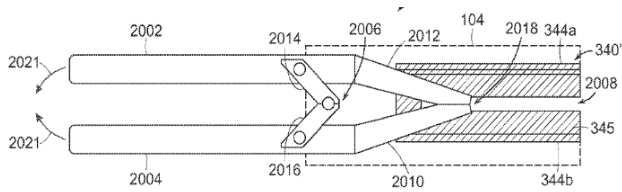


Figure 23: Mechanism closing according to the bell crank mechanism [75].

3.3.3 Mechanical meta-materials

Mechanical meta-materials are materials which behave unexpectedly if you would compare them with regular materials. The deformation of such mechanisms can be programmed in such a way, that the desired outcome of motion is achieved. One could consider meta-materials to be a sub-category of compliant mechanisms, but in literature these are seen as a category in itself. Also, for clarity the meta-materials are considered as a separate category as well. By varying the density of the meta material, the mechanism can have tunable mechanical properties.

Bending dominated
Bending dominated meta-materials are the most common type of meta-materials. These structures or lattices, mostly depend on deformation through bending. An example is a (non-parallel) gripper shown in Figure 24.

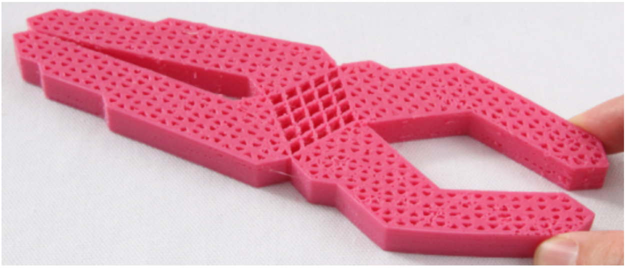


Figure 24: A non-parallel closing gripper made using a meta material structure [8].

The mechanical properties can be altered, by changing the relative density of the meta-material. This is the density of the material (ρ) divided by the density of the material when it's modelled as a solid block (ρ_s). By varying this density, the Young's modulus (E) and internal stress (σ) of the material changes according to the following relations [139]:

$$\frac{E}{Es} \sim \left(\frac{\rho}{\rho_s}\right)^2 \tag{4}$$

$$\frac{\sigma}{\sigma_y} \sim \left(\frac{\rho}{\rho_s}\right)^{1.5} \tag{5}$$

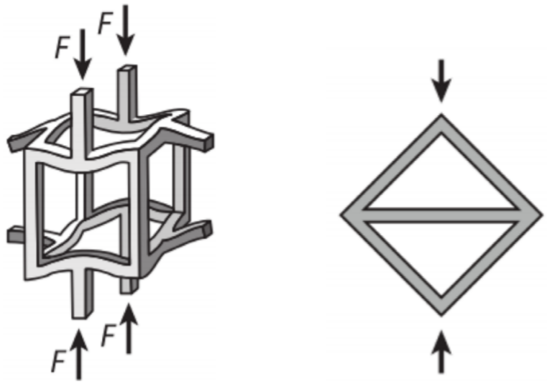
Stretching dominated
An example of a stretching dominated meta-material parallel closing mechanism has yet to be found. At the moment of writing this, no stretching dominated parallel closing mechanisms were found. The difference between bending and stretching dominated meta-materials is illustrated schematically in Figure 25. With bending dominated, the individual latticed are bent, while they are being stretched with stretching dominated meta-materials.

According to Surjadi et al. [139], the material properties for stretching dominated mechanisms change differently than bending dominated structures. The following relations can be derived for stretching dominated:

$$\frac{E}{Es} \sim \left(\frac{\rho}{\rho_s}\right) \tag{6}$$

$$\frac{\sigma}{\sigma_y} \sim \left(\frac{\rho}{\rho_s}\right) \tag{7}$$

Therefore, the influence of altering the relative density is less impactful on the overall flexibility and strength of the mechanism than with bending dominated meta-materials. Only a first order relation, while bending



(a) Bending dominated meta-material unit cell [139].

(b) Stretching dominated meta-material unit cell [139].

Figure 25: Different deformation methods for meta-materials.

dominated had a power of 1.5 and 2 for the Young's modulus and yield strength respectively.

Origami inspired
Origami inspired mechanical meta-materials has taken it's inspiration from the art of folding paper. No parallel closing origami inspired meta-materials were found whatsoever. However, the working principle is shown in Figure 26.

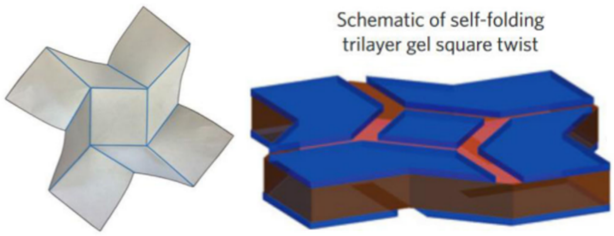


Figure 26: Origami inspired mechanical meta-material [139]. The right mechanism is derived from the art of folding paper (left).

Auxetic
Auxetic meta-materials have a negative Poisson's ratio ($\nu < 0$). No papers in this category meet the criteria for the search terms specified in the search methodology. However, the general working principle of the auxetic mechanical meta-material is shown in Figure 27. When compressing a material, instead of it becoming wider, it actually shrinks.

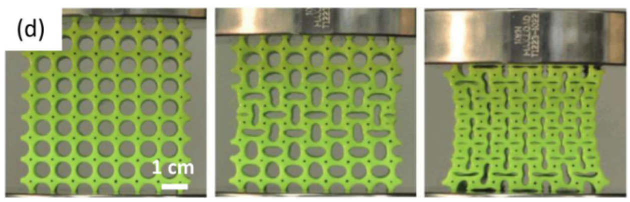


Figure 27: An auxetic meta material, having a negative Poisson's ratio thus bending inwards on compression [139].

3.3.4 Kinematic origami

Kinematic origami is the art of folding mechanisms. Kinematic origami separates itself from compliant mechanisms into a different category, because origami can actually fold itself and collapse. With compliant mechanisms, the range of motion is often quite limited, due to plastic deformation. According to Bowen et al. [14], there are two general types of kinematic origami to distinguish. The first one being open chain origami and the second network origami, using a closed chain folding pattern.

Open chain

Open chain kinematic origami does not contain a closed loop in the folding pattern. The left half of Figure 28 illustrates this schematically. The creases do not close the loop by coming back to the starting point of the loop.

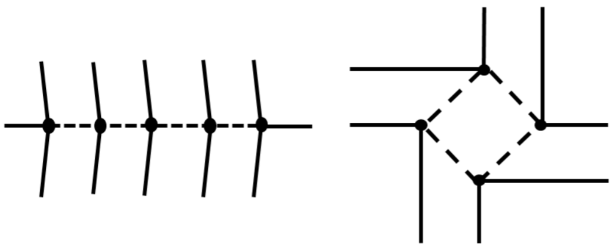


Figure 28: Folding patterns for kinematic origami, showing an open chain folding pattern on the left and a closed loop (network) on the right [14].

There was one paper found in this category, namely the paper by Liu et al. [98]. This paper researched the possibilities of open chain parallel closing mechanisms for Miura-ori structures. These kind of origami mechanisms can be folded from a flat sheet of paper. Figure 29 illustrates how these parallel closing origami structures can be made from paper. Six different configurations resulting in parallel closing of the structures. The mechanisms shown are folded from paper and modelled using zero-thickness surfaces, but a thick-origami prototype was also manufactured for the application of a parallel motion gripper.

Network

A closed loop folding pattern, as shown on the right of Figure 28, indicates that the origami is based on a network of creases. A network based origami structure is for example used by Zhang et al. [157], as shown in Figure 30. This is a basic parallel closing mechanism. There weren't as clear examples to be found as with open chain origami, although there were more papers found in this category.

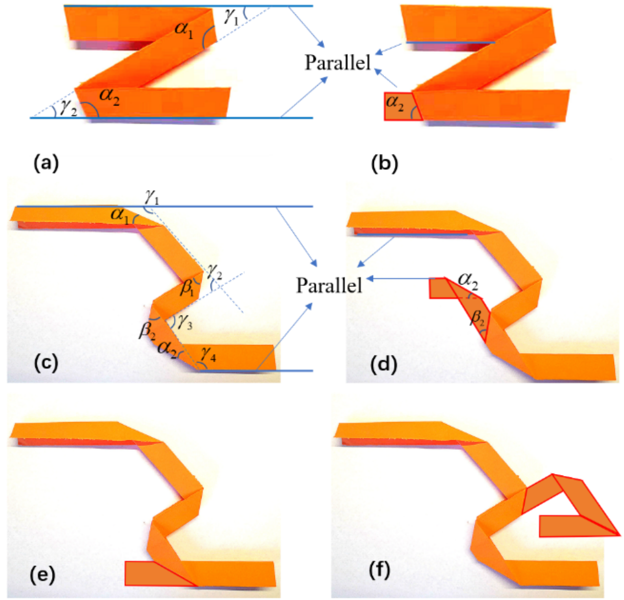


Figure 29: An example of parallel motion tips for Miura-ori structures: (a)(b)Extending the bottom strips inversely to create parallel-motion tips which towards inside; (c)(d)(e)(f)Three different ways to make the endmost tips heading inside. [98].

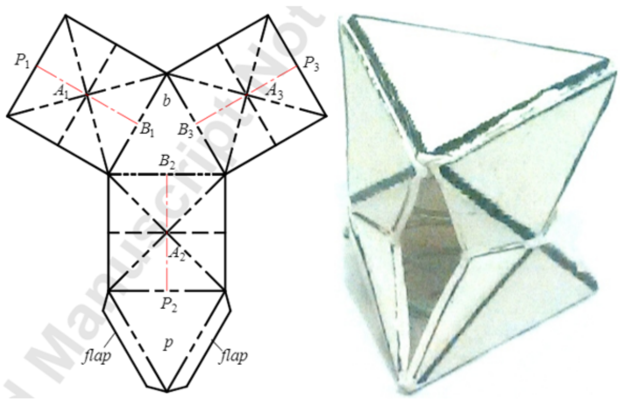


Figure 30: Parallel closing origami inspired mechanism [157].

3.3.5 Tendon-driven mechanisms

Tendon-driven mechanisms are mechanisms which are actuated by a system of cables and pulleys. This is a sub category, despite the fact that some mechanisms also consist of, for example, linkages. This is done to make the distinction more clear and because previous literature also makes this categorisation. The working principle of tendon-driven mechanisms can be divided into controllable- and uncontrollable mechanisms according to Ozawa et al. [119]. A combination of the two is possible as well.

Controllable

Controllable tendon-driven mechanisms can be controlled throughout their range of motion. The position of the end-effectors are fixed at every point in time. They can't move with respect to each other. The controllable group is in the minority with respect to the uncontrollable group. There were no clear figures to be found in literature, but with the controllable group, there must be at least two cables attached to each link in order for it to stay in a fixed position.

Uncontrollable

On the other hand, uncontrollable tendon-driven mechanisms have some degree of flexibility. They are popularly called 'under-actuated graspers'. However, the uncontrollable tendon-driven mechanism group consists of other categories as well and this is just one of the sub categories. Figure 31 shows an example of such an uncontrollable mechanism. Often, the tendon-driven mechanisms have multiple modes. For example an under-actuated grasping mode and a parallel grasping mode, sometimes also called a parallel pinching mode.

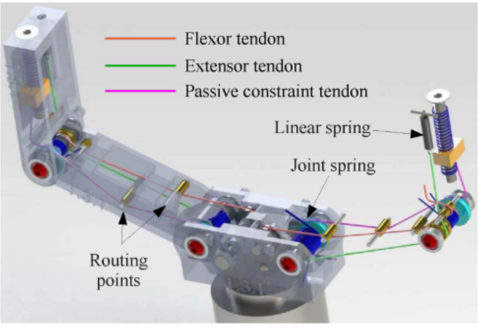


Figure 31: Uncontrollable tendon-driven mechanism [31].

Hybrid

Much like the hybrid category in the compliant mechanism group, a combination of controllable and uncontrollable links is also possible. These mechanisms were not found however, but the working principle should be clear based upon the explanations of the individual groups above.

3.3.6 Industrial grippers

The industrial mechanisms are not included in this literature overview for a couple of reasons. Their size is too big to be used in surgical instruments (they're often not well suited for geometric scaling). Due to the extension of this category, a whole separate literature study can be conducted on this topic. Also, what is often the case with industrial grippers, is that only the outside is visible. The inside of the gripper is a black box. In this literature review, the focus is on the working principles (the fundamentals) of parallel mechanisms. For completeness however, this category is included in the report, but not as extensively described as other categories. Collins [34] and Tsuchiya [144] provide categories for industrial gripper mechanisms. There are two main categories, namely the ones based on linear actuation and the other on rotary actuation.

Linear actuation

Linear actuation mechanisms can be divided into hydraulic, pneumatic and electro-mechanical actuation [23]. These types of mechanisms use a linear actuator to transfer motion.

Hydraulic Hydraulic actuation is using a fluid to achieve the transfer of forces. Most of the times, hydraulic actuation makes use of large piston cylinders. The downside of using hydraulic actuation instead of pneumatics - which will be discussed next - is that the fluid medium is slower compared to the movement of air. Both hydraulic and pneumatic cylinders are designed to push and mainly pull the load. They are not designed to transfer radial loads. The outside look of hydraulic and pneumatic cylinders resembles each other. An example of the housing is shown in Figure 32.

Figure 32: Linear actuator housings [34].

Pneumatic Pneumatic actuation is similar to hydraulic actuation, but with air as a force transfer medium instead. The downside is that air is compressible and therefore doesn't provide the amount of accuracy and responsiveness as using hydraulics would.

There is one interesting example found, which is not in itself useful for industrial grippers, but does belong in the pneumatic actuation category and that is the paper presented by Niiyama et al. [115]. This parallel gripper makes use of so called pouch motors for actuation instead of regular piston cylinders. These pouch motors are small, printable or inflatable soft actuators. Most often used in Robotics. Figure 33 shows a prototype of using the inflatable pouch motors.

Electro-mechanical Electro-mechanical actuated mechanisms are mechanisms which are directly driven by an electric motor. There are generally two types: screw-driven and belt-driven mechanisms [23].

Figure 33: Parallel gripper using a pneumatic pouch motor as actuation [115].

Screw-driven Two examples of screw-driven linear mechanisms are the gear and rack mechanism and the lead screw (often a trapezoidal thread) mechanism. A rotary motion of the screw is transferred into linear motion of the nut. This is shown schematically in Figure 34. This nut also has a spring tensioner, for reduced backlash and wear.

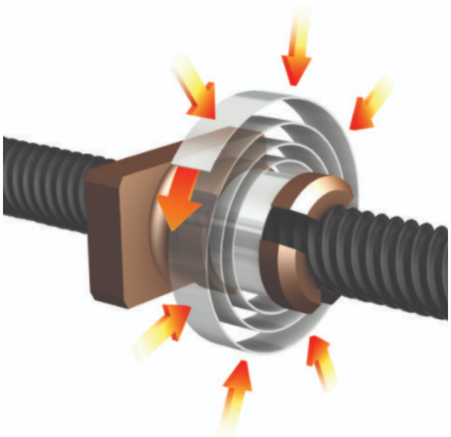


Figure 34: Linear actuation by means of a lead screw. [34].

Belt-driven Belt driven mechanisms are the other end of linear actuation. They are similar to screw-driven mechanisms in that a rotary motion of an axis is converted into linear translation on another axis. The difference is that instead of a mechanical connection between the two parts, now a timing belt is used to transfer the forces in the traverse direction. This is shown in Figure 35.

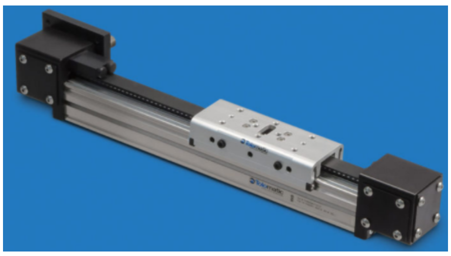


Figure 35: Linear actuation by means of a timing belt [34].

Rotary actuation

Rotary industrial grippers make use of a direct drive mechanism. The rotary motion of the electric motor is transferred to a rotary motion of the gripper. No examples of this category were included in this literature study. These kinds of mechanisms often use gears to obtain a certain transmission of the drive train.

4 Discussion

The field of parallel closing mechanisms and the extent of it have been mapped in this literature review. If the rate at which there are more papers being published each year continues, then the field will only become more prominent in the future. The results found in this study, the limitations and interesting points of discussion will be the topic of this section.

4.1 Distribution of found papers

The amount of literature found per publication year, as shown in Figure 6, shows an increase in the amount of relevant literature over time. This trend is a second order polynomial, but this is from a sample period only. If one were to compare all literature included, even from before 2000, a different trend line could be more correlating. But still, there is no denying in the fact that the parallel closing mechanism field is growing. It would be interesting to see how this growth would stand up against the natural growth of the total amount of published papers and seeing if there are any similarities.

An interesting distinction can also be seen in Figure 7. If the amount of papers found in the categories 'compliant mechanisms' and 'linkage mechanisms' are contrasted against the other categories, they make the other categories look diminutive. An explanation for this is not directly obvious. It could be due to the fact that these two categories - and in particular the linkage category - are older categories, which are already used quite a lot in everyday life. They are already documented in the past, over a longer time span than the other categories. These can be seen as relatively new, whereas linkage and compliant mechanisms become 'traditional' classical mechanisms. This is supported by the fact that there were some relevant papers found which had a publishing date of before 2000. These are not shown in the figure, because there are relatively few and this would only make the figure more unclear. However, all of these were linkage mechanisms, indicating that this is indeed the oldest category. The increase of relevant literature included over time is due to the fact that other categories were emerging.

An interesting spike around 2015 can be seen in Figure 6. This spike could be due to the fact that the compliant mechanisms were really upcoming since 2010. Especially since research takes a couple of years to develop. It could be that the compliant mechanism hype suffered from the novelty effect. Researchers were excited about this new technology and started publishing a lot papers, which can indeed be seen in Figure 7. Then, in 2018, the soft robotics group started to come up. There were some papers found in this category, but most of them were disregarded as most of them were not yet suitable for the application looked for in this study. Some spikes can also be from authors publishing more than one paper on the same research topic they are working on. It would be useful to identify this and also to map out certain research groups publishing a lot on the same topic. Some that stood out were Birmingham Young University (BYU) on the topics of compliant mechanisms combined with origami foldable structures. Delft University of Technology TUD does a lot of research into compliant mechanisms. The BITE group from TU Delft works a lot with tendon-driven mechanisms.

Also, during the search methodology, some filters were applied. These included publication year restrictions up to the year 2000 or 2010. Although these filters were not applied to all search queries, they could have had an influence on the outcome of the literature found. Therefore, the amount of papers per publication year are most accurate from 2010 onward. The influence was not that strong, as the first papers for meta-materials were published after 2016, for origami in 2013 and tendon-driven in 2012.

If currently upcoming research fields follow the same trend as compliant mechanisms did, i.e. following a rapid increase in amount of papers being published up to five years after the start, we can expect to see the amount of published papers related to parallel closing mechanisms increase the next couple of years. If the spike is around five years after the initial papers started showing up, we can expect to see a spike in 2024-25, in the meta-material and origami categories. These can influence the overall outcome of the amount of relevant literature for this study. If the amount of published compliant and linkage mechanism papers will keep growing too, the influence of the other categories is expected to be not as significant as the upcoming compliant mechanisms were.

4.2 Literature gap or abundance thereof?

The results of the classification shown in Figure 8 indicate that there is a literature gap in the following categories. First of all, a lack of research in the final design phase of parallel linkage mechanisms can be identified. Parallel mechanical meta-material grippers are an unexplored field in itself. There have been made some grippers with meta-materials in the past, but these were not parallel closing. Kinematic origami is upcoming, but most of the research is still in the conceptual phase, or design phase. Especially the open-chain kinematic origami is unexplored, but the one paper that was found, made it to a detailed design phase. As for tendon-driven parallel closing mechanisms, these are already used in some mechanisms, but an extensive study on the validation of these mechanisms doesn't exist.

On the other hand, there is an abundance of literature in the compliant mechanism group. Not only abundance, but also a lot of research made it to the final phase of the engineering design cycle. Especially in the MEMS group. That is interesting because linkage mechanisms have already been well integrated in society for a prolonged period of time, but is less well documented than compliant mechanisms which have only been around since the beginning of the previous decade (i.e. 2010 onward).

4.3 Pros and cons per category

Although caution has to be taken when talking about pros and cons, it is important to discuss these. Pros and cons can't be applied to an individual mechanism, but provide an overall impression of when to use a certain technology. A general description of what was mentioned in literature about the benefits and downsides of the particular type of mechanism is therefore useful indeed.

Compliant mechanisms often are bigger than their linkage mechanism counterparts. The design is more complex and will therefore be bigger to achieve the same motion. They also have a relatively low grasp-to-body ratio. Compliant mechanisms sometimes are not stiff or rigid enough for the application, but they do reduce any backlash and energy loss due to friction. They suffer more easily from plastic deformation than linkage mechanisms.

The function of parallel closing mechanisms is to generate a certain parallel motion. This can also be achieved by means of bar linkages. They are easy to model analytically, but arguably more difficult to model using FEA than compliant mechanisms. This is due to the contact surfaces between different bodies. Linkage mechanisms have proven to be a solid choice over time, as they are widely used in today's world. They are stiff and rigid, but also relatively heavy as there is no method for topology optimisation of linkage mechanisms, unlike with compliant mechanisms. Their grasp-to-body ratio is often very good, having a wide range of motion. There are more parts to manufacture and assemble, which is a downside of this category too.

Mechanical meta-materials share the same benefits and downsides as compliant mechanisms. The mechanical properties of these kind of mechanisms, can be altered, creating the motion that is desired. No optimisation tool was encountered to calculate the optimal densities of the mechanism. Both categories, metamaterials and compliant mechanisms, are often made in the 2D-plane. There's no expected increase in complexity of production. 3D-printing or Electrical discharge machining (EDM) are viable options for production in both categories, but there are more alternatives to be found for compliant mechanisms.

Kinematic origami is still in the early design phase. Most of the papers found were still in the conceptual design phase, using paper models as proof of concept. The category looks very promising, as the mechanisms are light weight and have a large range of motion, but nothing concrete could be found about stiffness or buckling resistance (e.g. using FEA) of the mechanisms. Little experimental data was found. The main concern would be stiffness and manufacturability. More research has to be done in these areas for this technology to become a more viable option.

Tendon-driven mechanisms have already started to develop a foundation of research. There are only few fully functional prototypes found and tested. Tendons provide a high range of motion, but stiffness and controlability can be an issue.

As the industrial grippers were not the main focus of this study, further research into these grippers has to be done in order to discuss some of the pros and cons of this category.

4.4 Grasp-to-body ratio

A few interesting claims were often made by papers in the linkage and compliant mechanism categories. A designed gripper had a so called "large jaw displacement" or similar formulations. Sometimes this is even put in the title of the paper. However, these are subjective and every reader has it's own expectations of 'large'. More often than not, papers who made this claim, had a jaw movement which was very small with respect to the total width of the mechanism. This important metric was often overlooked, but is very relevant as this is something you could expect to be very large, if you are reading the claim that was made.

The same is true for MEMS sytems. However, the literature term used in this category is: "a high amplification factor". The same wrong assumption can be made here. Often the mechanism itself is very bulky and made very rigid. This is not contributing to the overall grasp-to-body ratio, which is often not taken into account. It could be due to the micro-scale of the MEMS category, that this size is not important, as there's plenty of room to work with in the beginning.

4.5 Linkage vs compliant mechanism

When it comes to analysing compliant mechanisms, the analytical approach is to convert the compliant mechanisms to a PRBM mechanism and calculating the equations of motion from there. Finite element analysis (FEA) however, is directly applied to the mechanism. With linkage mechanisms, FEA is almost never done. Only an analytical method is presented, while there is an abundance of FEA found for compliant mechanisms. It would be beneficial to have more analysis done in the linkage mechanism area.

Generally, the parallel closing mechanisms can be divided into categories. There was no research done on combining different categories with each other. For example, a compliant linkage mechanism could have the best of both worlds. This approach should be further investigated, as it can lead to interesting mechanisms that are both rigid, stiff and don't suffer as much from wear and plastic deformation. Also, fewer parts means easier manufacturing and assembly. On critical points, where compliance is not suitable, a linkage can be used instead.

4.6 Origami inspired

Origami inspired mechanisms are relatively underdeveloped, but do provide promising mechanisms. Especially mechanisms which are inspired by Miura-ori, where a flat piece of material is folded into a mechanism. This is shown in Figure 36. It would be a nice addition to the current research, to create a similar mechanism that is parallel closing instead of v-shaped closing and can be folded from a plat piece of material (the animation on the right shows this for v-shaped closing).

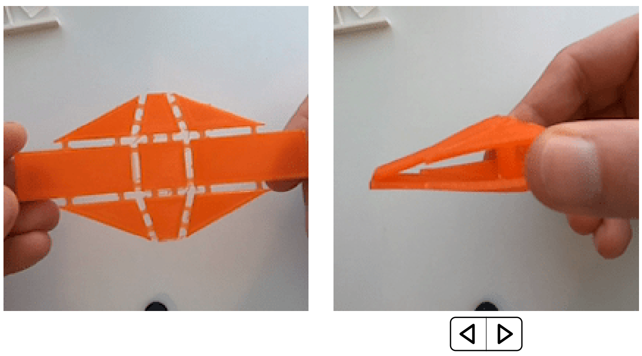


Figure 36: An animated figure, illustrating a non-parallel closing mechanism as example of a desired similar parallel closing mechanism. Prototype is 3D-printed using TPU. Mechanism is based on the work of Butler et al. [17].

4.7 Pneumatic revolution

Traditional industrial grippers generally involve heavy and bulky mechanisms. For example, pneumatic grippers use large piston air cylinders with a central rod pushing or pulling a certain load. They are also not designed to absorb radially induced loads. Research by Niiyama et al. [115] could potentially change both issues. The introduced pouch motors are also very small compared to their original piston counterparts. Pneumatic actuation now becomes more interesting to smaller mechanisms. They require much less geometric space, which is often the barrier preventing pneumatics to be used in such mechanisms. The pouch motors are illustrated in Figure 37. A parallel closing gripper has also been manufactured.

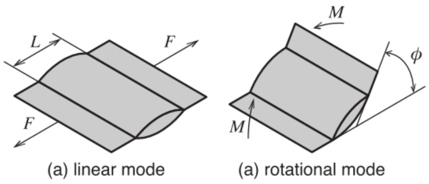


Figure 37: Pouch motors presented by Niiyama et al. [115].

4.8 Future research

The research in this literature review is specifically oriented towards parallel closing mechanisms. This is a niche in the literature.

To make this research complete, a similar approach has to be taken on parallel industrial grippers. This category is briefly discussed and a proposed classification is made. However, the literature for this category has not yet been included due to it's extent and the time constraints of this literature review. A separate literature review can be made of the industrial gripper category, as it's often not clear what is inside the mechanisms. The outside and specifications are shown, but the design itself remains a black box.

It is beyond the scope of this study to address the question of what kind of actuation mechanisms are existent. It would be useful to do this literature review again and classify each actuation method for parallel closing mechanisms. That way, the actuation methods are classified also, which does supplement this research well.

The same can be said about the design and manufacturing methods. It will be a nice addition to this research, to gain insight in the design and manufacturing methods for each type of mechanism. This can be built on top of the current existing classification presented in this literature review.

Further research is required to establish if there are any gaps in industry to be found. A categorisation of papers according to their application using the Global Industry Classification Standard (GICS) [56] would be beneficial to show in which sector certain types mechanisms are used and in which not. This is a more practical oriented research, but is valuable to show the potential of applications in a different sector than where they are used.

In nature, parallel closing mechanisms can also be found. Problems which researchers are facing nowadays, might have already been solved by nature. Years of evolution have optimised certain mechanisms. One such example is a bird's skull. A large parallel linkage mechanism is present, as can be seen in Figure 38. What's interesting is that although the bird's skull

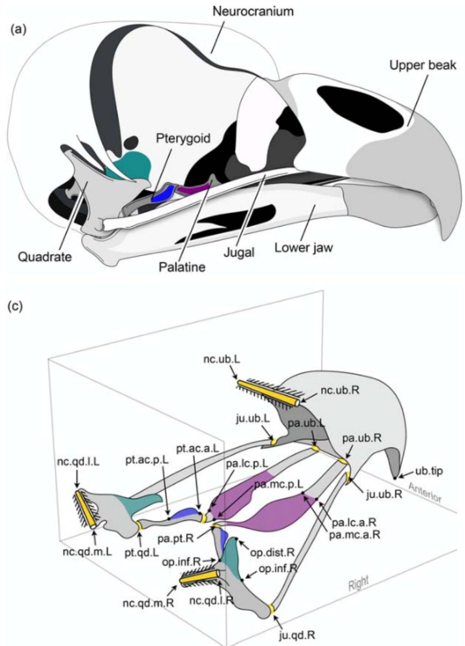


Figure 38: Linkage mechanism found in the skull of a bird [118].

makes use of rigid links, much like the linkage mechanism category, there are no hinges used. In fact, there is no direct connection between the linkages at all. They are held in place with tendons and muscles. This is not implemented yet in everyday mechanisms. Further research on how to apply these mechanisms found in nature to everyday technology would be very interesting indeed. It might even lead to a new category in the classification scheme.

The controllability in terms of output force and displacement and compatibility with the environment of the gripper is also missing in a lot of papers. It is important though, to have a gripper that is intuitive to control towards the user. Especially with medical applications, the compatibility with the biological environment has to be taken into account. Design papers could also put more effort in making a cost estimation of the mechanism and try to reduce it as much as possible.

5 Conclusion

The aim of this literature review was to map out the state-of-the-art parallel closing mechanisms in a systematic classification scheme. The research had to be reproducible, which means that every step during this study is well documented. Multiple search engines were used to make sure there was a wide coverage of research databases. The structure of this paper is derived from previously peer-reviewed literature. The findings of the study will be used for designing a strong, foldable beak able to close in parallel, which is part of the DAPCA project. It will eliminate the problem of peak stresses, tissue being pushed outward and a too long end effector.

The search methodology consisted of four phases defined by the PRISMA statement, namely: identification, screening, eligibility and included. The effectiveness of each of the nine search queries is calculated with a custom made tool written in Python. A total of 163 research papers were included in the classification, resulting in a total effectiveness of the search queries of 4% (4040 papers were identified).

A novel two-dimensional functional classification scheme has been made. This classification consists of six main categories: compliant mechanisms, linkage mechanisms, mechanical meta-materials, kinematic origami, tendon-driven mechanisms and industrial grippers. The categories were based on the literature that was found. Each of these categories are then divided into sub categories, based on previous published literature of the parent category. This resulted in a total of 18 sub-categories, some of which even have separate branches for specific literature areas which ought to be highlighted.

An extra dimension is added to the classification by classifying the literature in each of the categories, into different phases of the engineering design process. There were four design phases chosen: conceptual, detailed design, verification and validation.

There is a growing interest in parallel closing mechanisms, as there is more research published on this topic each year. Compliant mechanisms and linkage mechanisms are the biggest categories, the other categories are still in the early phase of research.

The research area of parallel closing mechanisms had never been mapped out before. From now on, if there's a need to finding a specific type of parallel closing mechanism, this systematic literature review will provide the necessary state-of-the-art classification.

6 Author's comments

This section describes additional points of discussion which did not fit directly in the discussion section of the results. They may or may not be directly related to the results of this study, but they are relevant for the topic of parallel closing mechanisms and are interesting to take into consideration.

6.1 Relevancy ranking

It is questionable what certain search engines define as relevant. Some search engines want to give you the results that contain the keywords you sought for, while others try to find the articles that could potentially answer your question. A formidable candidate of the latter is Google Scholar. Google might be quite biased for a systematic literature review, it has its own algorithm to determine what is relevant for you. Also, it bases its search on your previous searches (history) and location. It would be best to always turn geometric location off and use incognito mode when doing a systematic literature review.

An interesting side note on Google Scholar, is that only United States (US) patents could be found. If this is the case, it would mean that the search engine is indeed biased. It could be that there are more US patents requested, but given the fact that Google is an American company, it could be that it's not showing EU or other country's patents for some reason. No information on this topic could be found. Google also provides a dedicated Patent database. It would be useful to check if this database does contain non-US patents.

6.2 Other options for mechanisms

Mechanisms that were not encountered in this study were bi-stable mechanisms. These mechanism could have added value, especially in the medical industry, as the surgeon for example doesn't have to apply a pressure to close a clip applier. If the bi-stable mechanism closes by itself and snaps into place, the closing pressure will always be the same. This will also avoid putting excess strain on the surgeon's hand.

What's also not often done with parallel closing mechanisms, are normally open or normally closed mechanisms. These have as added benefit that you only have to actuate one direction of the degree of freedom of the mechanism and the mechanism will automatically return to it's original position. Compliant mechanisms do have a neutral position, but this usually is the closed configuration, or close to this configuration.

Although the papers which are being discussed below did not make it into the classification for parallel closing mechanisms specific, they did provide an interesting addition to the design of such mechanisms. For example, [141] and [153] showed that for a gripper assembly, you don't have to have two moving jaws. You could only have one jaw moving and the other one standing still, resulting in one-sided clamping. The jaw that's not moving can then be part of the housing of the gripper or any other fixed point.

Other interesting mechanisms, including both regular and parallel closing mechanisms, are shown in the following videos from THO and Veritasium.

6.3 Additional discussion parallel closing mechanisms

It can be argued that parallel closing mechanisms also induce a form of translation as the mechanism closes. This is however acceptable, if not desired, if the translation is forward, so that the object that is being grabbed is pushed to the back of the beak. If this is not desired, a countermeasure can be taken in the form of a motion inverter mechanism.

A single actuation degree of freedom for parallel closing mechanisms is desired, but not a strict requirement. This also doesn't have to be a fluent motion. A mechanism with a step-wise actuation, incrementing a movement by multiple strokes, is acceptable. This mechanisms wasn't encountered during this literature review. In the case of a medical device, the lever action has to be one staged, i.e. using only one actuation input and not multiple handles or anything like that.

Mechanisms could also benefit from a dynamic range of motion. For example using a switch for different modes of the mechanisms, but incorporated in the mechanism itself would be even better. One mode could be bridging large displacements with only very little force and the other one small displacements with the possibility to transfer high forces. This will result in better control and larger range of motion with the same input displacement.

Lateral forces on grippers also have to be considered. Often these are not modelled, as the researcher is only interested in the motion and force transfer in the 2D plane. But it would be good to at least have some thought put into this, for example by analysing the eigenfrequencies of the mechanisms. These forces can probably be neglected because they are so small compared to the in plane forces, so it isn't considered as important to take into account during the design phase.

The added benefit of closing mechanisms in parallel, is that the teeth on v-shaped closing grippers don't have to be present anymore. Because the item is no longer pushed outward, there's no need really to try and improve the friction force, possibly with the risk of damaging the object that is being grabbed. This is of course assuming that the matter of grasping grip due to friction in general is satisfied. Besides that, the force along the beak of the gripper is now evenly distributed. With v-shaped closing, the gripping force increased from the tip to the end of the beak, where it is maximum. So in the case of the latter, where you grab an item is really important, as it determined how much gripping force you can apply. This is much more intuitive with parallel closing, as this force is the same irrespective of where the item is grabbed.

6.4 Industries

Parallel closing mechanisms are used in lots of fields. Examples are home appliances, grippers and deployable mechanisms. It would be very interesting to map the applications of all the categories according to the Global Industry Classification Standard (GICS) [56]. This would give insight in where certain types of mechanisms are used and where they potentially could provide added value. The outer space sector/industry is doing a lot of research into foldable origami structures. They have to be lightweight, stiff and stowage efficient, making origami very promising in this sector. The medical field mainly uses linkage mechanisms for surgical devices. There are almost no compliance mechanisms to be found in this sector, while they seem promising for this application. They have fewer parts and therefore easier to clean than their counterparts - the linkage mechanisms. MEMS systems are used as micro-grippers.

The medical field can be discussed in depth if access is granted to a report from 360researchreports.com. This report shows a prediction of laparoscopic instruments in the medical sector, up to the year 2024. This includes the size of the sector, the amount of money in circulation and predictions of what kind of clip appliers are necessary and where.

6.5 MLEM mechanisms new standard for laparoscopic surgery?

It is standard for laparoscopic devices to have a round shaft. Although round is usually considered as optimal state for strength and stiffness, it is not the best shape for minimally invasive surgery. Changing the shape of these shafts is arguably disruptive, but can have some benefits. For example, the MLEM mechanisms have a flat but wide configuration. Although they are wider than the round shafts, the total cross sectional area might even be the same since they can be made very thin. Figure 39 illustrates this schematically.

This is now a simple optimisation problem, to find a common area of the two devices, which can be described

Figure 39: A simple optimisation problem for the cross sectional surface of minimally invasive surgery devices. The left is using a regular round shaft and the right is an MLEM mechanism.

by the following relation:

$$A_1 = A_2 = \pi \cdot r^2 = w \cdot h \tag{8}$$

Where r is the radius of the round surface and w and h are the width and height of the flat shaft respectively.

However, this is not all. During surgery, when an incision is made with a scalpel, the incision is thin and relatively long. Putting a round shaft through the incision will stretch it open, possibly even tearing the corners of the incision. A flat, wide shaft does not have this problem, as it happens to have roughly the same shape as the incision. This could possibly even be beneficial for the healing process and prevention of scarring.

6.6 Design and manufacturability

A rather interesting finding was that after the initial selection of papers, during the full text analysis, a lot of papers which were excluded during that list went in depth about the design and manufacturing methods of (parallel) closing mechanisms. They did not go in depth into the mechanisms of interest for this literature review, but they did provide valuable information about how to manufacture (parallel) closing mechanisms. In particular, the compliant mechanisms category showed a large amount of papers going in depth about design methods and manufacturability of compliant mechanisms, which is of interest for parallel closing mechanisms. They also discuss the limitations in design methods. That's where the relevance for this literature review comes in. These assets are also applicable for parallel closing mechanisms. Table 3 gives an overview of the papers going in depth about these categories. Topology optimisation is another subject that was encountered a lot. Such an extensive list wasn't found for any of the other categories. This would be beneficial to have, but is out of scope for this literature review.

Topic	Literature references
Design and manufacturing	[159][162][49][94][13] [83][84][50][86][74][54] [51][122][96][146][82]
Topology optimisation	[7][161][97][133][93][6] [82][101][51]

Table 3: Papers about the design and fabrication methods of compliant mechanisms.

One side note is that these papers did miss two manufacturability methods for prototyping. The first being the use of spring leafs. This in combination with laser-cutting Polymethylmethacrylaat (PMMA) and some superglue can be a good way to do early prototyping. One such an example is shown in Figure 40. One paper found is using a similar method for prototyping[94].

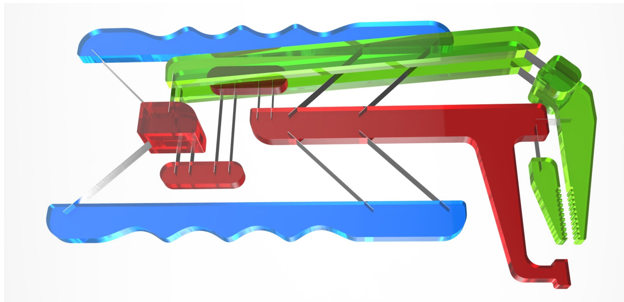
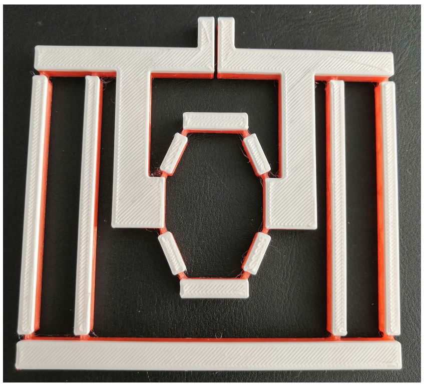


Figure 40: Prototype of a compliant non-parallel gripper mechanism - an unbuttoning aid by [42].

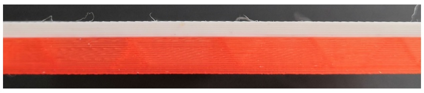
The second method overlooked for prototyping and testing, is using 3D-printing techniques. While these methods are already used in some papers, the design method of using flexible filaments, e.g. TPU, isn't. Printing using two different materials, one stiff material and one flexible, provides an even more interesting early prototyping method. If one would for example use PLA for rigid links and TPU for the flexible hinges or links, a cheap validation mechanism can be built. An example is shown in Figure 41. The adhesion layer is the critical point of failure in these kinds of mechanisms. These can however be improved by using form closed connections between the two. Using two print nozzles would also be ideal so you don't have to switch between the two materials.

6.7 Topology optimisation

A lot of papers on this topic of topology optimisation were found. Some of which also contained examples of parallel closing mechanisms, therefore they were not excluded from this study. Table 3 shows an overview of these papers. These papers use a so called multiple input multiple output (MIMO) approach. At first, in- and output points are defined, and the ratio between the input and output displacement. A bounding box is then created, using the maximum amount of bounded space, including areas which have to remain unobstructed. After that, an algorithm calculates the optimum topology based on these constraints. This is a very interesting tool for parallel closing mechanisms and can be applied directly to any compliant mechanism. Figure 42 shows the design space with boundary



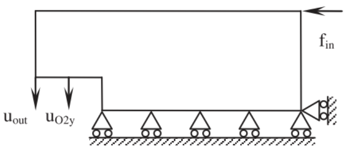
(a) Top view of the parallel closing mechanism.



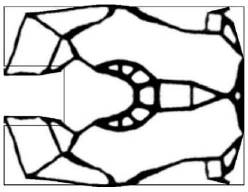
(b) Side view with good layer adhesion between PLA (white, top) and TPU (orange, bottom).

Figure 41: Modified 3D-printed version of the mechanism presented in [61], using TPU for flexibility and PLA for rigidity.

conditions and the resulting optimum topology.



(a) Design space for topology optimisation. MIMO system with boundary conditions.



(b) Optimal result.

Figure 42: Topology optimisation of a parallel closing mechanism [101].

These kinds of tools could only be found for compliant parallel closing mechanisms. There was no such tool found for linkage mechanisms or any other category, while it would be interesting to research these possibilities in future research.

6.8 Recommendations

Figures can in some situations explain more than words can do. However, sometimes even figures fall short to explain for example the predicted motions that a certain mechanism will make. Its good to have the explicit inverse kinematic equations of an end-effector when modelling a particular gripper, but it really doesn't put things into perspective. In that case, it would be best to make a simple animation showing the result of the equations: the movement of for example the bar linkages. It would be nice to have a standard way of reporting these mechanisms. Compare the left and right of Figure 22. Which one does have the preference? Specialised software can be used for this purpose. Using Flash Player to achieve this, is not a good idea. The future of this software is uncertain and is generally supported less over time, to a point where, somewhere in the foreseeable future, it's no longer supported anymore. The animations made in this paper are made using an animated sequence of .PNG files, written in JavaScript, using the animate LaTeX package. This will still be supported in the future. It would be beneficial if more papers would use this preferred method to describe the working principles of their mechanisms.

On a different note, the GSQUIP program presented in this paper has shown it's potential. With hindsight, the 0% effectiveness of the first search query showed that this query could have been left out, if it was identified beforehand. This can help with identifying effective keywords with minimal overlap, resulting in a better literature review and saving time in the process. This tool has provided a basis for future literature reviewers to work with and to improve. The program is not optimised and can be upgraded a lot. Especially the support for other search engines than Google is missing. The GSQUIP program can be made more extensive by making it more versatile, i.e. the program should be able to analyse different search engines and compare the results with each other. For an improved version, it would be useful to consider using Scrapy instead of Selenium as framework for data scraping the titles and other data from search engines. This was, however, out of scope for this paper.

It also showed that Google uses an approximation to estimate the amount of search results found and that there are duplicated found of the same article, slightly differently formulated. It would be beneficial if these were filtered out by Google.

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A Search queries numerous search engines

Table 4 shows the search queries used for other search engines than Google Scholar. The table is in analogy with Table 1.

Table 4: Search strategy keywords and results with inclusion and exclusion criteria. WoS = Web of Science, PM = PubMed, SP = Scopus, TUDR = TU Delft Repository, WSQ = Web Search Query

WSQ			Exact phrase	And	Year	NOT	Language	Results			Selected		
WoS	PM	SP						WoS	PM	SP	WoS	PM	SP
1	1	1	Parallel closing mechanism			"non-parallel"	GB, NL, DE, FR	1	1	1	1	1	1
2	2	2	Parallel clamping	mechanism OR gripper OR device		"non-parallel"	GB, NL, DE, FR	2	0	5	2	0	3
3	3	3	Parallel closing	mechanism OR gripper OR device		"non-parallel"	GB, NL, DE, FR	1	1	2	1	1	1
4	4	4	Parallel gripper			"non-parallel", "statically balanced", "motion platform","constant-force", "parallel manipulator"	GB, NL, DE, FR	59	0	117	6	0	8
5	5	5	Parallel grasping	mechanism OR device OR gripper		"non-parallel"	GB, NL, DE, FR	15	0	32	4	0	7
6	6	6	Parallel linkage	mechanism OR device OR gripper		"non-parallel", "statically balanced", "motion platform","constant-force", "parallel manipulator"	GB, NL, DE, FR	29	7	100	0	1	2
7	7	7	Clip applier	parallel		"non-parallel"	GB, NL, DE, FR	0	0	3	0	0	0
8	8	8	Compliant gripper	parallel		"non-parallel", "statically balanced", "motion platform","constant-force", "parallel manipulator"	GB, NL, DE, FR	5	0	92	3	0	4
9	9	9	Origami gripper	parallel		"non-parallel"	GB, NL, DE, FR	0	0	17	0	0	1
Total								112	9	369	17	3	27