A design procedure for conceptual design of mechanisms

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Abstract: In this paper, a design procedure for conceptual design of mechanisms is presented as finally applied to robotic legs. This method is based on topological synthesis and reassembly analysis. A topological synthesis is elaborated by providing a complete atlas of each basic function element with a basic function; while a reassembly analysis is worked out to give a sufficient number of design candidates by reassembling basic function elements in a proper way. The proposed procedure provides a limited number of design candidates and it avoids a generation of unfeasible isomorphic kinematic chains, so that the process of conceptual design in terms of kinematic structure is considerably reduced both in computation time and efforts. Two examples are discussed with the aim to validate the presented approach.

Keywords: design procedure; conceptual design; mechanism design; topological synthesis, reassembly analysis; leg mechanism; suspension mechanism.

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1 Introduction

In general, design work for mechanisms conception can be divided into two categories: design of new mechanisms; design of mechanisms with topological structure of existing ones but aiming at avoiding infringing patents. A design process can be logically divided into three interrelated phases, (Tsai, 2001): product specification and planning phase, conceptual design phase, and product design phase. In product specification and planning phase, design specifications in terms of functional requirements, structural requirements, and design constraint will be clarified. In conceptual design phase, it is convenient to generate as many design candidates as possible, and then these candidates will be evaluated against design specifications, and finally the most promising solution will be selected for the next product design phase.

As pointed out by Chakrabarti and Bligh (2001), conceptual design phase is an important phase in developing mechanical devices. Researchers have developed many approached for conceptual design of mechanisms. Graph theory has been widely used for an abstract representation of kinematic structure (Crossley, 1965; Freudenstein and Maki, 1983) and for automating the process of mechanism type selection (Soni et al., 1988). However, theoretic graph approaches required an initial configuration in order to start the enumeration of all possible kinematic chains. Kota and Chiou (Kota and Chiou, 1992; Chiou and Kota, 1999) proposed a qualitative matrix scheme for conceptual design of mechanisms. The approach was developed as based on decomposition of functional requirements in matrix forms and combination of identified kinematic building blocks. Zu et al. (2009) reported a method for automated conceptual design of mechanisms by using enumeration and functional reasoning. This approach is capable of working out all the possible and feasible combined configurations for desired function requirements with a given number of building blocks in a pre-build knowledge base, as well as it is useful to filter out unfeasible solutions. In addition, Wang and Yan (2002) proposed a computerised rules-based conceptual design approach for complex mechanisms; Han and Lee (2006) reported a case-based method for reusing previous design concepts in conceptual synthesis of mechanisms; Pucheta and Cardona (2007) proposed an automatic procedure based on the construction of an 'initial graph', which rejects thousands of unfeasible subgraph occurrences searched inside a kinematic chain until finding a given result. However, it is just suitable for 1-DOF mechanisms. Many researchers realised that during the conceptual design phase of mechanisms, a proper way for providing sufficient independent design candidates of mechanisms is structural synthesis of kinematic chains as pointed out in Hung et al. (2008). Since types of topological structures are as many as species of creatures in nature, for structural synthesis, a synthesis method must have the characteristics of effectiveness, automation and designer-friendliness as pointed out by Al-Dweiri et al. (2010). Ding et al. (2012) proposed a method which is at once effective, automatic and designer friendly for synthesising all the valid topological structures of planar 1-DOF kinematic chains only. This method is based on a graph and corresponding contracted graph representation of kinematic chains (Gross and Yellen, 2006), together with new methods of detecting isomorphism and rigid sub-chains (Ding et al., 2010). By using this method, researchers can get a complete atlas database of 1-DOF kinematic chains in a fairly simple procedure. But there are still open problems.

A synthesis of kinematic chains is not the only issue in design process of mechanisms. Once atlas of all kinematic chains are generated, it is needed to specify kinematic links and joints and then to particularise them in order to obtain practical mechanical devices. In 1998, Yan (1998) proposed a creative design method of mechanical devices, which provides computer procedure for number synthesis of kinematic chains and it also illustrates the concept for specialisation and particularisation of feasible kinematic chains. However, this method is based on existing designs, but for the design of new mechanisms, further development is needed. Li and Ceccarelli (2011) reported a topological search for new leg mechanisms by using Yan's method. It can be seen that the process is somehow time-consuming due to the complex operation of specialisation and particularisation. Furthermore, some unfeasible solutions were generated yet. In 2001, Tsai (2001) reported a systematic design methodology as based on graph theory and combinatorial analysis. The approach is suitable for both kinds of design works mentioned above. However, these methods have a common problem, which is that they will generate a large number of kinematic chains. For example, as reported by Ding et al. (2012), for 1-DOF kinematic chains which have 6, 8, 10 and 14 links, the corresponding numbers of topological graphs in the atlas databases are 2, 16, 230, and 318,162, respectively. It is fairly easy to generate so many chains thanks to automatic computations. However, since specialisation and particularisation cannot be done automatically at present, it is definitely time-consuming to evaluate out so many candidates into mechanical devices since the process is on manual basis.

This paper is focused on a new method for conceptual design of mechanisms with more efficient procedure. This method is based on topological synthesis and reassembly analysis for achieving final solutions. It is supposed to be systematic and efficient, since it can deal with design of both simple and complex mechanisms, no matter whether there are existing designs. The proposed procedure can avoid generating a large number of unfeasible isomorphic candidates, so that it can shorten the process of conceptual design of mechanical devices. In addition, the method proposed in this paper is handled manually, and it is not only for the design of 1-DOF mechanisms. It is also suitable for mechanisms with more than 1-DOF though the examples are both of 1-DOF mechanisms.

2 Description of the new proposed procedure

In this section, a new proposed procedure is formulated and explained in detail. Main steps can be outlined as:

- Step 1: to identify design specifications according to customer's requirements.
- Step2: to characterise topological characteristics of existing designs or preliminary solutions that can satisfy the design specifications.
- Step 3: to adopt the approach reported by Yan (1998)in order to generate atlas of design candidates if the existing designs or preliminary solutions are simple mechanisms; Otherwise, to determine how many basic functional elements (BFEs) that the mechanism can be divided into according to the design specifications.
- Step 4: to divide the mechanism into BFEs and generate a complete atlas of each BFE.
- Step 5: to use reassembly analysis to generate new design candidates.
- Step 6: to evaluate each design candidate in order to exclude unfeasible isomorphic ones.
- Step 7: to obtain the atlas of all feasible solutions.

Figure 1 summarises the procedures outlined in the abovementioned seven steps, with details that are explained in the following paragraphs.

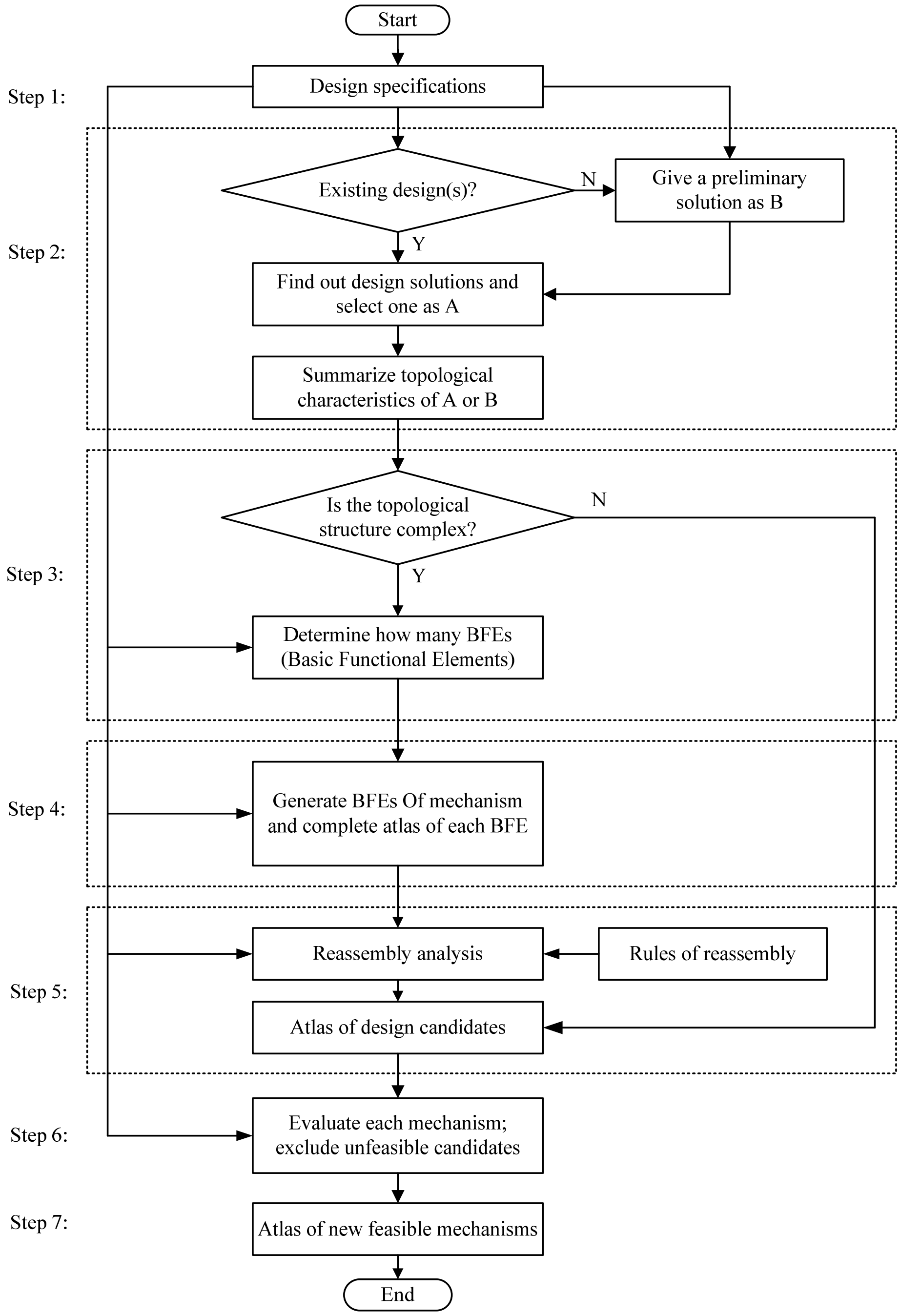
Design specifications mentioned in Step 1 for conceptual design are parsed into three coherent categories, namely functional requirements, structural requirements, and design constraint (Chen and Pai, 2005). After the specifications are identified, it is needed to search whether there are existing designs that can satisfy them. If so, topological characteristics of the existing designs are summarised in Step 2; if not, a preliminary solution needs to be sketched by the designer. Then, topological characteristics of this preliminary proposal need to be summarised also.

In Step 3, different operations are carried out according to the complexity of the existing mechanisms or preliminary solutions. Thus, first it is needed to indicate how to judge the complexity of a mechanism. In the following, (m, n) denotes a mechanism with m links and n joints. As can be deduced from Yan's (1998) approach, if there are too many chains in the atlas of a (m, n) generalised chain, the implementation of specialisation and particularisation workouts will be time-consuming. Namely the approach is not efficient if there are too many chains in the atlas of a (m, n) generalised chain. Due to this reason, complexity of a (m, n) mechanism can be judged according to the quantity of chains in the atlas of the (m, n) generalised chain. Thus, in order to judge the complexity, a critical value CV for the number of chains can be set as

$$CV = M \tag{1}$$

where M is fixed by the designer as the limit value.

Figure 1 A flowchart for a new design procedure for conceptual design of mechanisms



In such a way, a mechanism is defined as simple mechanism if it has less than M chains in the atlas of its generalised chain. Otherwise, it is complex. For example, if M is fixed as 3, mechanisms with link and joint configurations of (3, 3), (4, 4), (4, 5), (4, 6), (5, 5), (5, 6), (6, 6), (7, 7), and (8, 8) are simple mechanisms because all of them have less than 3 chains in their atlas of generalised chains; whereas mechanisms with link and joint configurations of (5, 7), (6, 7), and (6, 8) are complex because they have 3 or more chains in their atlas of generalised chains. The critical value M is chosen by designers according to their experience, analysis goals, and design constraints. Nevertheless, for a better usage of this new method, M is recommended not to be more than 5, since when a mechanism has more than five chains in its atlas of generalised chains, it is better to be divided into BFEs.

A BFE mentioned in Step 3 refers to an element that has a basic function (BF) as obtained from the existing mechanisms or preliminary designs according to design specifications and it cannot be divided into smaller ones. BF can be frame, input, output, transmission, shock absorber, or similar elementary functions. BFE could be a link with one or more than one joints, a closed or open chain that is composed by several links and joints, or similar function components. It is remarkable that a mechanism can be divided into different groups of BFEs according to different design specifications. Once design specifications are specified, how many BFEs that a mechanism can be divided into can be determined according to the specifications. However, in any case, the operation of dividing mechanism into BFEs must comply with

$$\sum_{1}^{j} L_i = m \tag{2}$$

$$\sum_{1}^{j} J_{ia} + \frac{1}{2}\sum_{1}^{j} J_{ib} = n \tag{3}$$

in which i = 1, …, j, and j is the number of the BFEs which compose a mechanism; Li is the number of links of the i^{th} BFE; m and n are the number of links and joints of the mechanism; J_{ia} and J_{ib} are the number of internal and external joints of the i^{th} BFE, respectively. Internal joints of one BFE are the joints used for connecting the links of this BFE, while external joints are the joints used for connecting this BFE to other BFEs.

In Step 4, numbers of links, internal and external joints of each BFE need to be clarified aiming at generating complete atlases of all BFEs. Equations (2) and (3) can be used to determine the number of internal and external joints. It is noteworthy that the members in the atlas of one BFE could have different number of links and joints. This will be better illustrated in the reported examples.

Before reassembly operation, isomorphic external joints of each BFE should be identified with the aim to avoid isomorphic design candidates. Reassembly analysis in Step 5 can be considered as the reverse process of Step 4. It is used to combine the BFEs obtained in Step 4 into design candidates according to rules of reassembly. General rules of reassembly can be outlined as:

- Topological characteristics of design candidates that are obtained through reassembly operation should be consistent with those of the existing design A or preliminary solution B.
- For each group of isomorphic joints, reassembly operation should only be worked out once.
- There should be no isolated external joints existing after reassembly operation.

In addition, when doing reassembly operation, if there is a BFE that works as a frame with several joints, this frame will be sketched as several separated fixed joints rather than a single link with several joints. Moreover, the reassembly operation must be mechanical reasonable. For example, one link cannot be connected to a frame by two joints otherwise this link will be fixed on the frame. Such a reassembly operation is convenient to obtain design candidates since designer just needs to choose groups of BFEs from atlases of the BFEs first and then to join them together following the rules of reassembly in order to form design candidates. The description of the proposed procedure will be strengthened through two examples as reported in the next section.

3 Cases study

In this section, two examples for designing new off-road motorcycle suspension mechanisms and new LARM leg mechanisms are reported to illustrate the implementation of the proposed approach and to verify its feasibility and efficiency.

3.1 Case study 1: design of off-road motorcycle suspension mechanisms

Figure 2(a) shows a HONDA pro-link suspension mechanism, which is composed of one mounting bracket, one rear shock absorber, one swing arm, one shock link, and one shock arm as illustrated in the figure. In particular, Stephenson and Wattlinkages are used in the mechanism. In the kinematic scheme shown in Figure 2(b), numbers 1, 2, 3, 4, 5, and 6 represents the mounting bracket, shock link, swing arm, shock arm, piston rod and cylinder (these two parts constitute the rear shock absorber), respectively. Besides, A, B, C, D, E, F are six revolute joints and G is a prismatic joint. Furthermore, it is a single DOF mechanism. Thus, topological characteristics can be outlined as:

- It consists of 6 links and 7 joints (6 revolute joints and 1 prismatic joint);
- It is a 1-DOF mechanism.

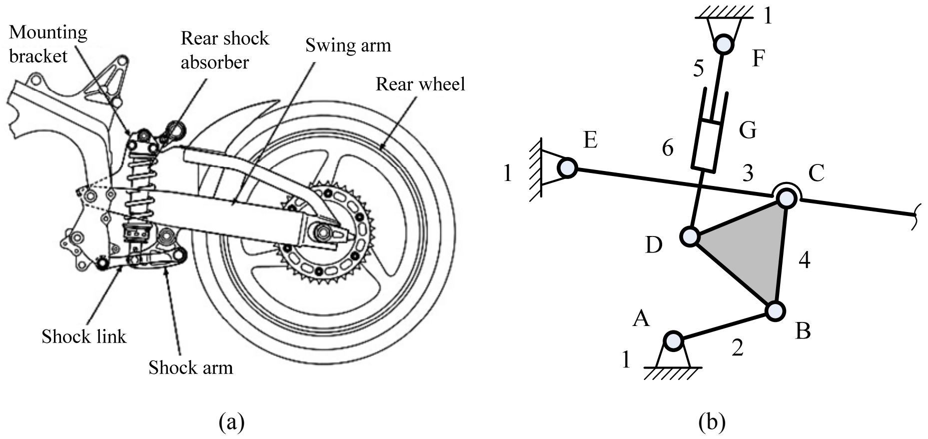
The goal is to design new suspension mechanisms that have same topological characteristics as the one in Figure 2 and can avoid infringing patents of present designs. Design specifications can be identified by looking at the main components and there functionalities.

The mechanism has 6 links and 7 joints. From the book of Yan (1998), there are three chains in the atlas of a (6, 7) generalised chain, so that it can be considered as a complex structure according to equation (1) with critical value M equals to 3 and the suspension mechanism can be divided into three BFEs:

- BFE1: shock absorber
- BFE2: Frame link
- BFE3: a chain composed of a swing arm, a shock arm, and a connecting link.

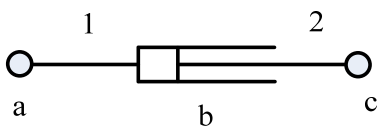
When dividing the suspension mechanism into these three BFEs, the shock absorber, namely BFE1 can be obtained firstly as shown in Figure 3. It consists of two links and three joints, which are two revolute joints and one prismatic joint. Obviously, the prismatic joint is internal joint, while the two revolute joints are external joints. Thus, $J_{1a} = 1$ and $J_{1b} = 2$.

Figure 2 An existing design solution of off-road motorcycle suspension mechanism (HONDA pro-link), (a) a mechanical scheme (b) a kinematic scheme



Notes: 1 – mounting bracket; 2 – shock link; 3 – swing arm; 4 – shock arm; 5 – piston rod; 6 – piston cylinder; A, B, C, D, E, F – six revolute joints; G – prismatic joint

Figure 3 BFE1: shock absorber



Notes: 1, 2 – links; b – an internal joint; a, c – two external joints.

In BFE2, there is only one link, which is the frame link, thus there is no internal joint, namely $J_{2a} = 0$. Whereas in BFE3, there are three links, thus BFE3 must be an open chain, because a closed chain composed of 3 links just can be considered as 1 link. In addition, there must be 2 internal joints in an open chain composed of 3 links, namely $J_{3a} = 2$. In order to make the mechanism a 1-DOF mechanism, frame link should have at least 2 joints. Supposing it has 2 joints [Figure 4(a)], i.e., $J_{2b} = 2$, the number of external joints of BFE3, i.e., J_{3b} can be determined according to equation (3) as

$$J_{3b} = 2n - 2\sum_{1}^{3} J_{ia} - \sum_{1}^{2} J_{ib} \tag{4}$$

in which n = 7, which is the number of joints of the suspension mechanism, thus $J_{3b} = 4$, which indicate that BFE3 has four external joints. In this case, two types of BFE3 can be obtained as shown in Figure 5(a) and Figure 5(b). In another situation, supposing BFE2 has 3 external joints, i.e., $J_{2b} = 3$ [Figure 4(b)], J_{3b} can be calculated according to equation (4) and the result is 3.In this case, another two types of BFE3 can be obtained as shown in Figure 5(c) and Figure 5(d). Moreover, if $J_{2b} = 4$ [Figure 4(c)], J_{3b} can be calculated according to equation (4) and the result is 2. In this case, another type of BFE3 can be obtained as shown in Figure 5(e). Thus, two atlases of BFE2 and BFE3 are obtained as in Figures 4 and 5, respectively.

Figure 4 An atlas of BFE2, (a) with two external joints (b) with three external joints (c) with four external joints

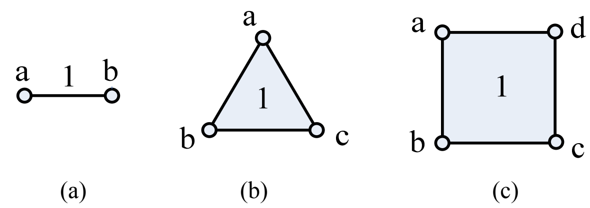
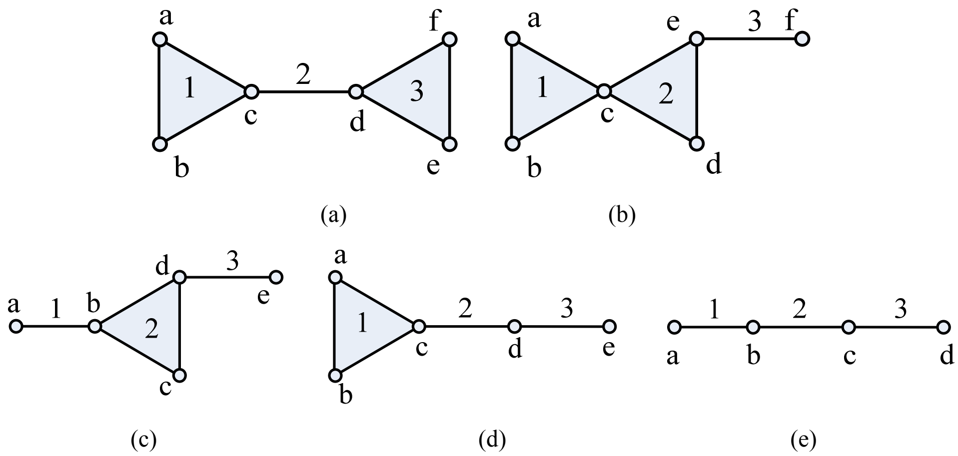


Figure 5 An atlas of BFE3, (a) and (b) an open chain with four external joints; (c) and (d) an open chain with three external joints; (e): an open chain with two external joints



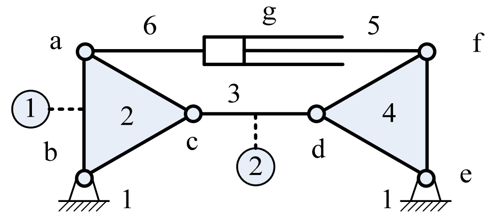
After obtaining the atlas of every BFE, reassembly operation can be implemented. Since topological characteristics of the design candidates obtained through reassembly operation should be consistent with that of the existing design, and the reassembly groups need to satisfy equations (2) and (3), configuration of reassembly groups can be organised as in Table 1.

Table 1 Configuration of reassembly groups

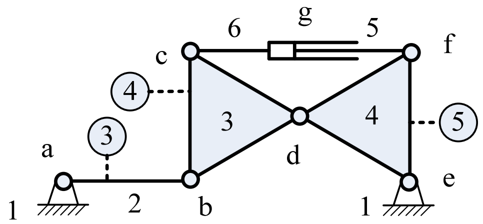
Group 1	Figure 3	Figure 4(a)	Figure 5(a)
Group 2	Figure 3	Figure 4(a)	Figure 5(b)
Group 3	Figure 3	Figure 4(b)	Figure 5(c)
Group 4	Figure 3	Figure 4(b)	Figure 5(d)
Group 5	Figure 3	Figure 4(c)	Figure 5(e)

During reassembly operation of each group, in order to avoid generating isomorphic mechanism and meanwhile save time, it is necessary to identify if there are isomorphic joints among the external joints of each BFE. As in Figure 3, external joints a and c are isomorphic joints. In BFE2, all the joints of the frame link are isomorphic joints. As in Figure 5(a), joints a, b, e and f are isomorphic joints; in Figure 5(b), a and b are isomorphic joints; in Figure 5(c), joints a and e are isomorphic joints; in Figure 5(d), joints a and b are isomorphic joints; and in Figure 5(e), joints a and d are isomorphic joints.

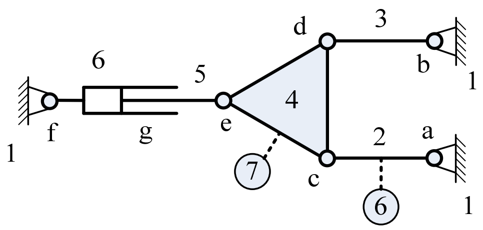
Figure 6 An atlas of possible design schemes obtained from the reassembly groups in Table 1, (a) to (d) obtained from group 1 to 4, respectively



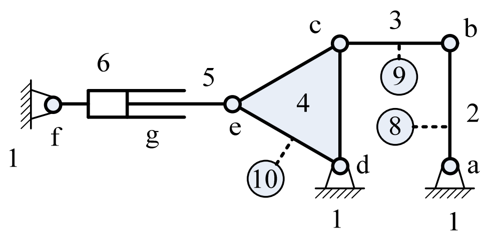
(a)



(b)



(c)

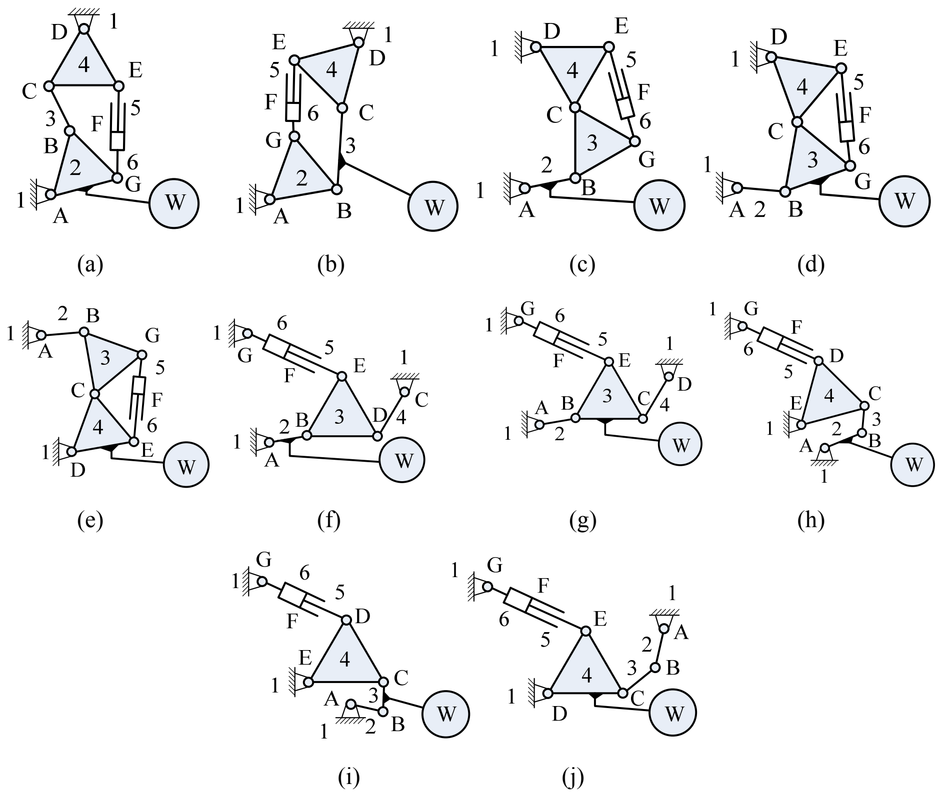


(d)

Following the rules of reassembly operation, for group 1, 2, 3, and 4, corresponding kinematic chain can be obtained as in Figures 6(a) to 6(d) with frame sketched in form of fixed joints, respectively. Group 5 is unfeasible since in this configuration, all external joints of both BFE1 and BFE3 need to be fixed on ground, which will lead to unreasonable structure from mechanical point of view.

For each solution in Figure 6, rear wheel of the motorcycle can be assembled on links 2, 3, or 4. Thus, after excluding isomorphic structures [in Figure 6(a), 2 and 4 are isomorphic links; in Figure 6(c), 2 and 3 are isomorphic links], ten possible solutions could be assembled as marked in Figure 6. Finally, 10 design candidates are obtained as shown in Figure 7. Figure 7(f) is the structure of the HONDA pro-link (Figure 2). After excluding this and other existing designs, an atlas of new design candidates can be obtained. Those are new kinematic structure solutions including the active modular groups with 1 DOF. The concept of active modular groups has been used also in Comanescu et al. (2008).

Figure 7 An atlas of possible design candidates, (a–b) obtained from Figure 6(a); (c–e) obtained from Figure 6(b); (f–g) obtained from Figure 6(c); (h–j) obtained from Figure 6(d) (W: rear wheel)



3.2 *Case study 2: design of LARM leg mechanisms*

This example was presented with preliminary results in Li and Ceccarelli (2011) by using the method proposed by Yan (1998). Several new design candidates were obtained and reported in that article. However, the process was not so efficient and user-oriented because unfeasible solutions were generated, and the operation of specialisation and particularisation were fairly time-consuming.

The LARM single DOF leg mechanism is composed of a Chebyshev linkage ABCDE and a pantograph mechanism EFGHJ, as in Figure 8. The Chebyshev mechanism ABCDE is the input driving mechanism, which is used for generating suitable ovoid curve at point E as characteristic for human-like walking. In particular, AC is a crank, BD is a rocker, and CDE is a coupler. Joint at pivot points A and B are fixed on the frame of the mechanism. The pantograph mechanism EFGHJK is used as leg to amplify the input trajectory of point E into output trajectory with the same shape and an amplified scale at point K. Topological characteristics of the leg mechanism can be outlined as:

- it consists of 8 links and 10 joints: one frame link (1), one crank (2), three rockers (3, 6, and 7), two transmission links (4 and 5), one output link (8), and 10 revolute joints (A–J)
- it is a 1-DOF mechanism.

In order to make the comparison between this new method and Yan's method, more reasonable design specifications are set the same as those in the preliminary work (Li and Ceccarelli, 2011), i.e., design specifications are identified as:

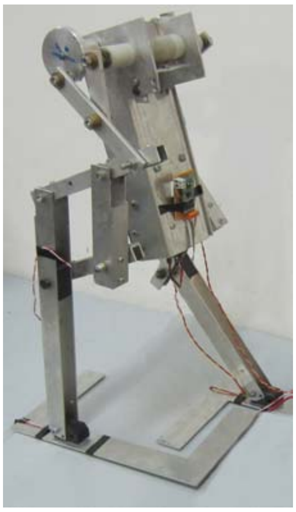
- there should be a Chebyshev four-bar linkage working as an input mechanism
- there should be a pantograph mechanism used for amplifying the input trajectory and outputting it as the foot trajectory.

After the identification of topological characteristics, it is needed to judge if the mechanism is complex by using the strategy indicated in Section 2. First, it is known that the mechanism has 8 links and 10 joints. Then from the book of Yan (1998), there are 16 chains in the atlas of a (8, 10) generalised chain, so that it can be considered as a complex structure according to equation (1) with M specified as 3. Thus, it needs to be divided into BFEs. According to design constraints (Li and Ceccarelli, 2011), the leg mechanism is characterised by a Chebyshev mechanism and a pantograph mechanism, therefore it can be divided into3 BFEs, manually:

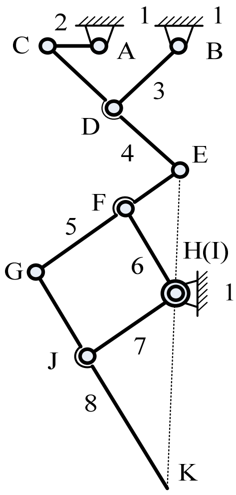
- BFE1: pantograph mechanism
- BFE2:Chebyshev four-bar linkage
- BFE3: frame.

While dividing the LARM leg mechanism into BFEs, pantograph mechanism, namely BFE1 can be easily obtained since it is independent of frame link. External joints a, b, c and internal joints d, e, f of BFE1 are indicated in Fig. 9. What calls for special attention is that number of external joints between links 2 and 3 is two, i.e., joints b and c, which overlapped each other. That is because links 2 and 3 need to be connected to another link through the overlapped joints in order to make the mechanism as a pantograph mechanism. Thus, $J_{1a} = 3$ and $J_{1b} = 3$.

Figure 8 An existing design of leg mechanism composed of a Chebyshev mechanism and a pantograph mechanism at LARM, (a) a prototype (b) a kinematic scheme (see online version for colours)



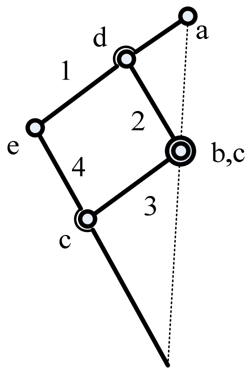
(a)



(b)

Notes: 1 – frame link; 2 – input link; 3 – rocker a; 4 and 5 – transmission links a and b; 6 and 7 – rockers band c; 8 – output link

Figure 9 BFE1: pantograph mechanism



Notes: 1–4: links; a, b and c: external joints; d and e: internal joints.

Chebyshev mechanism has strict proportion between its links, as indicated in Figure 10(a). Distance between external joints a and b should be guaranteed when they are connecting to BFE3, i.e., the frame. For BFE2, number of internal joint $J_{2a} = 2$. Number of external joints depends on how it will be connected to BFE1. If BFE2 will be connected to joint a of BFE1, the number of joint at point e is one [Figure 10(a)]. If BFE2 will be connected to joint b and c of BFE1, the number of joint at point e is two [Figure 10(b)]. Based on the analysis, two types of BFE2 are obtained as shown in Figure 10(a) and Figure 10(b), respectively. Corresponding types of BFE3 are obtained according to equation (2) and equation (3) as in Figure 11.

Figure 10 An atlas of BFE2, (a) with 1 output joint: e (1–3: links; c and d: internal joints; a, b and e: external joints); (b) with 2 output joints: e and f (1–3: links; c and d: internal joints; a, b, e and f: external joints

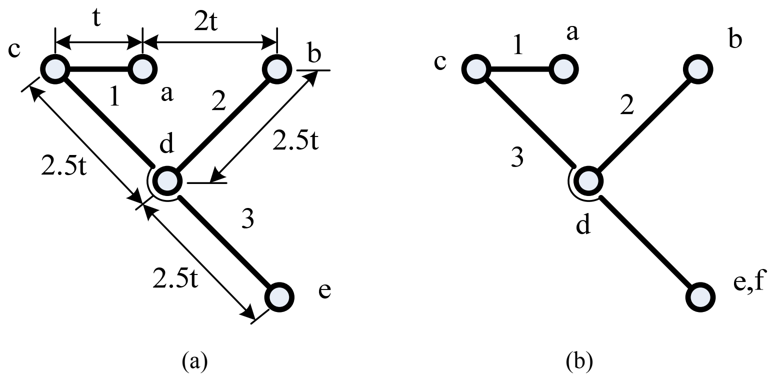
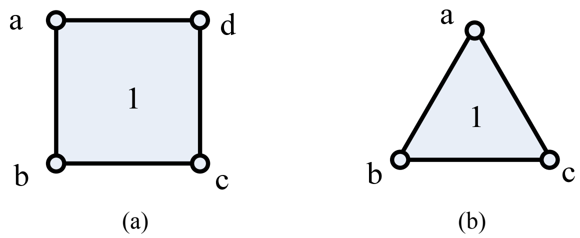


Figure 11 An atlas of BFE3, (a) with four external joints (1: link; a–d: external joints); (b) with three external joints (1: link; a–c: external joints)



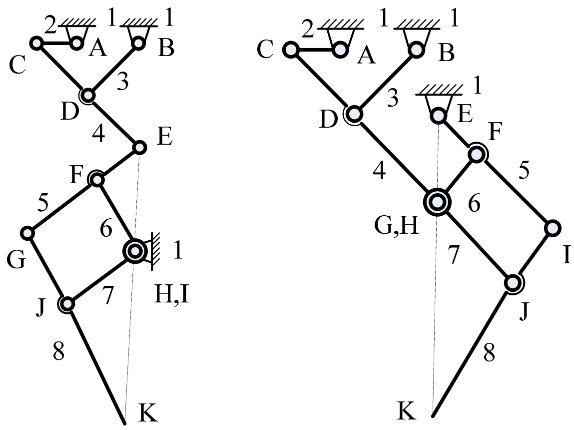
Then reassembly operation is carried out following rules of reassembly. To do this, first it is needed to clarify the reassembly groups. The reassembly groups are generated according to equations (2) and (3). There are two groups of configuration as listed in Table 2. Finally, an atlas of design candidates, which contains two leg mechanisms, is obtained as in Figure 12.

Table 2 Configuration of reassembly groups

Group 1	Figure 9	Figure 10(a)	Figure 11(a)
Group 2	Figure 9	Figure 10(b)	Figure 11(b)

After the atlas of the design candidates is obtained, each candidate is evaluated against design specifications aiming at excluding unfeasible and isomorphic candidates from the atlas. Since design specifications are considered from the beginning to the end of the method, there are no unfeasible and isomorphic candidates generated as indicated in Figure 12. In addition, comparing to the previous work proposed by Li and Ceccarelli (2011), the method in this paper looks fairly simpler since it does not need specialisation and particularisation processing with manual inspection.

Figure 12 An atlas of all the feasible design candidates of the leg mechanisms, (a) with a amplification ratio of EH/HK (b) with a amplification ratio of EK/EH



(a) (b)

4 Conclusions

A new systematic method for conceptual design of mechanisms has been proposed as based on topological synthesis and reassembly analysis with computational efficiency aspects. Topological synthesis provides atlases of BFEs divided from the existing designs or preliminary solutions. Reassembly analysis enables quick constructions of these BFEs into design candidates. This method has three novel features:

- It is systematic because it can deal with design of both simple and complex mechanisms, no matter whether there are existing design solutions or not.
- It is efficient because it can provide sufficient number of design candidates and meanwhile avoid unfeasible and isomorphic candidates thanks to the use of design specifications throughout the whole process.
- Reassembly analysis enables quick construction of design candidates.

The feasibility, efficiency, and the abovementioned novel features of the proposed method have been validated by two examples, namely for new off-road motorcycle suspension mechanisms and new LARM leg mechanisms.

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