Dan Zhang · Bin Wei *Editors*

Dynamic Balancing of Mechanisms and Synthesizing of Parallel Robots

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ISBN 978-3-319-17682-6 ISBN 978-3-319-17683-3 (eBook)
DOI 10.1007/978-3-319-17683-3

Library of Congress Control Number: 2015947930

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

Preface

As the emerging technologies of robotics, dynamic balancing for mechanisms and parallel robots has become one of the bottleneck issues for the applications in modern manufacturing industries, space, medical industries, military, and social service. Research and development of various dynamic balancing methods is now being performed more and more actively in every applicable field. This book will introduce state-of-the-art research in these technologies from theory to practice in a systematic and comprehensive way.

Any vibrations in mechanisms will cause inaccuracy while they are in operations. Traditional counterbalance methods make the whole mechanism heavier and have more inertia; the book entitled *Dynamic Balancing of Mechanisms and Synthesizing of Parallel Robots* will be the first book that describes the up-to-date technologies in dynamic balancing of mechanisms and parallel robots. It systematically and thoroughly not only deals with different dynamic balancing principles but also comprises recent advances on dynamic balancing of mechanisms with minimum increase of mass and inertia, synthesizing of parallel robots based on decomposition and integration concept, and finally optimization and control issues for balancing are discussed at length within this book.

We would like to express our deep appreciation to all the authors for their significant contributions to the book. Their commitment, enthusiasm, and technical expertise are what made this book possible. We are also grateful to the publisher for supporting this project and would especially like to thank Ms. Merry Stuber, Editorial Assistant of Springer US, and Ms. Lesley Poliner, Springer US Science and Business Media Project Coordinator, for their constructive assistance and earnest cooperation, both with the publishing venture in general and the editorial details. We hope the readers find this book informative and useful.

This book consists of 20 chapters. Chapter 1 introduces the recent advances on reactionless mechanisms and parallel robots, and the dynamic balancing through reconfiguration concept is proposed. Chapter 2 presents methods and principles used for balancing of planar mechanisms without counterrotations. Chapter 3 considers the shaking moment and shaking force balancing through the use of additional Assur groups mounted on the mechanism to be balanced. Two types of mechanisms are considered, the in-line four-bar linkage and the planar parallel robots with prismatic pairs. Chapter 4 discusses the development of reactionless planar parallel manipulators by using base-mounted counterrotations and inertia flywheel rotating with a prescribed angular velocity. Chapter 5 introduces a new general method to find the dynamic balancing conditions based on the use of natural coordinates for planar mechanisms, and the method has been shown in its application to the design and dynamic balancing of plane mechanisms. Chapter 6 deals with the shaking force and shaking moment balancing of single degree of freedom planar mechanisms by employing the traditional technique of addition of counterweights and counterrotating inertias. Chapter 7 proposes a force balancing method called adjusting kinematic parameters for robotic mechanisms or real-time controllable mechanisms. Chapter 8 proposes a formulation, which can be seen as a tool in selecting appropriate solution(s) according to the expected operation conditions, to address the effects of balancing on mass distributions and dynamic performance. A case of study has been developed by referring to a three degrees-of-freedom spatial parallel manipulator by designing proper counter-rotary counterweights. Chapter 9 focuses on dynamic balancing with respect to a given trajectory for the parallel link robots by modeling control system. Chapter 10 addresses the class of problems that require movement of a dynamic bipedal system according to stringent state-space and temporal requirements despite actuation limits and disturbances. Chapter 11 presents an optimization technique to dynamically balance planar mechanisms by minimizing the shaking forces and shaking moments due to inertia-induced forces. Chapter 12 investigates the dynamic response of mechanism having revolute joints with clearance, and a 4R four-bar mechanism whose two joints have clearances is considered as a model mechanism. Chapter 13 minimizes the shaking force and moment fluctuations at the planar mechanism by employing the genetic algorithm. Chapter 14 presents the optimal balancing for the open-chain robotic system based on the indirect solution of open-loop optimal control problem. Chapter 15 studies the dynamics and control of planar, translation, and spherical parallel manipulators by means of the constraint equations. Chapter 16 deals with the dynamic modeling and control of balanced parallel mechanisms, highlights the importance of the dynamic modeling process, and discusses the impact of the dynamic model, developed in accordance with the methodology, for the control strategy of parallel mechanisms. Chapter 17 describes the control principles necessary for an articulated biped model to accomplish balanced locomotion during walking and climbing. Chapter 18 focuses on the control of a 10-dof biped robot, and a spline-based control system is described in order to generate the servo inputs. Chapter 19 deals with an approach to formulate balancing conditions for the shaking force and shaking moment of planar mechanisms and spatial mechanisms. Chapter 20 addresses the static balancing of six degree-of-freedom articulated wheeled vehicles with multiple leg-wheel subsystem.

Finally, the editors would like to sincerely acknowledge all the friends and colleagues who have contributed to this book.

Oshawa, ON, Canada Dan Zhang
December 2014 Bin Wei

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Chapter 1
Review of Recent Advances on Reactionless Mechanisms and Parallel Robots

Dan Zhang and Bin Wei

Abstract When parallel mechanisms are in motions, because the center of mass (CoM) is not fixed and angular momentum is not constant, vibration is often produced in the system. Shaking force and shaking moment balancing can usually be realized by making the CoM of mechanism fixed and angular momentum constant. There are generally two main ways for shaking force balancing and shaking moment balancing, balancing before kinematic synthesis and balancing at the end of the design process. For the balancing at the end of the design process, addition of counterweights and counter-rotations, addition of active dynamic balancing unit, and addition of auxiliary links are mostly used methods. The advances and problems on dynamic balancing of mechanisms are discussed in detail under the above two main categories here, and balancing through reconfiguration method is proposed, which can reduce the addition of mass and inertia. Fisher's method belongs to the method of balancing before kinematic synthesis.

Keywords Parallel mechanisms • Momentum • Dynamic balancing • Reconfiguration

1.1 Introduction

Parallel mechanisms have been broadly used in the areas of machine tools, telescopes and space, etc., but a problem occurs when they are in operations; it is not dynamic balanced, which affects the accuracy performance when mechanisms are in the process of operations. When mechanisms move, as the center of mass (CoM) of the mechanism is not fixed and angular momentum is not constant, vibration is usually produced in the system. Dynamic balancing can usually be achieved by making the linear and angular momentum of the mechanism constant. The research for dynamic balancing of parallel mechanisms is still in its early stage. Since 2000

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D. Zhang, B. Wei (eds.), *Dynamic Balancing of Mechanisms and Synthesizing of Parallel Robots*, DOI 10.1007/978-3-319-17683-3_1

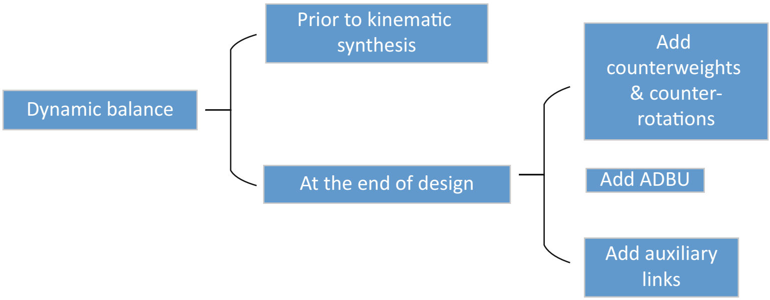

Fig. 1.1 Two main categories for dynamic balancing

when scholars Ricard and Gosselin systematically addressed the dynamic balancing of parallel mechanisms [1], dynamic balancing began to appear more and more in the academic arena. In order to achieve dynamic balance, force balance and moment balance need to be both satisfied at the same time. Force balance is a subset of static balance, which means when the mechanism is force balanced, it is also static balanced, and the mechanisms can remain stable without any actuator forces. Traditionally counterweights are used to achieve force balance, i.e., make the CoM fixed, and counter-rotations are used to make the angular momentum constant. Force balance and moment balance are all about using extra devices (e.g., counterweights, counter-rotations) to counterbalance the shaking force and moment that the original mechanism exerted, but the whole mechanisms will become heavier and have more inertia when using those counterbalancing devices. How to design reactionless mechanisms with minimum increase of mass and inertia has become a common desire. There are generally two main ways for shaking force and shaking moment balancing, i.e., "balancing before kinematic synthesis" and "balancing at the end of the design process" as shown in Fig. 1.1. Here dynamic balancing based on two main categories is discussed in details, and a new balancing principle concept is proposed, the advantage of which is that addition of counterweights can be reduced. For the category of balancing at the end of the design process, addition of counterweights and counter-rotations, addition of active dynamic balancing unit (ADBU), and addition of auxiliary links are mostly used methods; for the category of balancing before kinematic synthesis, Fisher's method is a typical example of this.

For the shaking force balancing, for example, when a link is rotating round a pivot, because CoM of the link is not still, so the link will have a shaking force, when a counterweight is added to the extendable part of that link, then the CoM of the whole link is fixed in the revolute joint, and it is force balanced. If the counterweight is added, the system will become heavy. The second method is to employ ADBU; the ADBU will create a shaking force and shaking moment that the value of which is equal but has opposite direction to the original shaking force and shaking moment so that it can counterbalance those original unbalanced conditions. The third method is to add auxiliary links; the mass of additional link can be used to force balance, for example in [2], all the mass of the moving platform and part of the mass of the links attached to the moving platform for the three-dimensional delta robot. In addition, Fisher's method can also be seen as the method of addition of auxiliary links. Here balance through reconfiguration concept is proposed; for example, we can use screw link so that the link can be moved, the CoM of the link then can be moved to the revolute joint, and then it is balanced; in this method counterweight is not applied but through reconfiguration of the system by moving the screw link the system will not become heavy. For the shaking moment balancing, addition of counter-rotation method, addition of CRCM method, using inherently dynamic balanced 4-bar linkage method, and addition of ADBU method are mostly used principles.

1.2 Prior to Kinematic Synthesis

1.2.1 Dynamic Balanced 4-Bar Linkage

In [3], a 4-bar linkage was proposed to synthesize three degrees of freedom parallel manipulators. By serially connecting two 4-bar linkages, a 2-DOF reactionless serial mechanism was constructed, and the 2-DOF mechanism was used to build the 3-DOF parallel manipulators. The advantage of the above mechanism is that it did not employ counter-rotations, but the drawback is that moving platform is assumed thin, which is not practical. The above 4-bar linkage is actually derived from the principle vector linkage. The three-serial-chain principle vector linkage is evolved to a 4-bar linkage by adding a base link to the ground as shown in Fig. 1.2, and by finding the moment balancing conditions for the 4-bar linkage, the dynamic balanced 4-bar linkage can be derived.

In [4], a 3-DOF serially connected mechanism was derived from two 4-bar mechanisms and one composite mechanism. This 3-DOF mechanism can be used as leg to construct the spatial 6-DOF parallel manipulators. The composite mechanism is derived from a pair of 4-bar mechanisms that orthogonally fixed each other. Because the author wanted to design a spatial 6-DOF parallel manipulator, which requires the 4-bar linkage to move spatially, and due to the fact that the 4-bar linkage is not dynamic balanced when moving spatially, the composite mechanism is developed. Also the synthesized mechanism as shown in Fig. 1.3 is proposed by connecting the 4-bar linkage or composite mechanism to the end bar of the base 4-bar linkage, and the synthesized mechanism was verified that it was dynamic balanced, which is done by the following: if the resulting parameters of the end bar of the base 4-bar linkage and attached mechanism (this attached mechanism can be 4-bar linkage or composite mechanism) meet the balance condition, then the synthesized mechanism will be dynamic balanced.

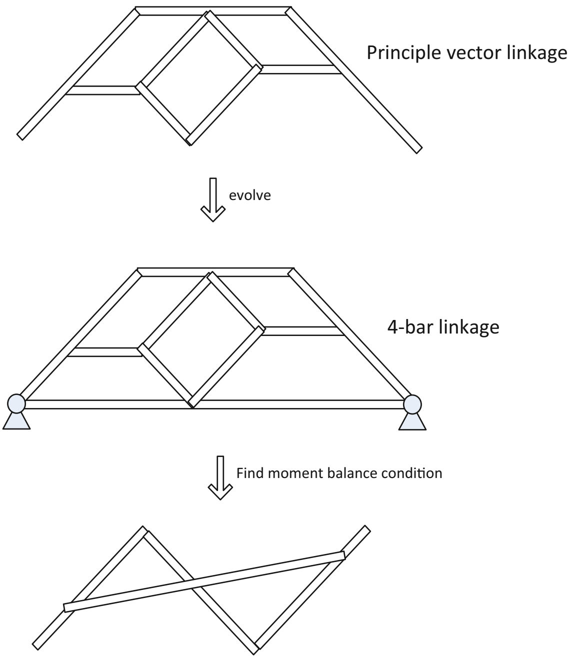

Fig. 1.2 Evolve process for deriving the dynamic balanced 4-bar linkage

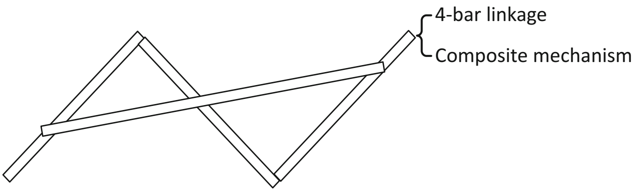

Fig. 1.3 Synthesized mechanism

1.2.2 Fisher's Method

V.D. Wijk has thoroughly investigated this method in his PhD thesis and papers [5–7]; the core content can be concluded as follows: for the shaking force balance, first determine the linear momentum, then determine the force balance condition from the linear momentum, and finally determine the principle dimensions. For the 2-DOF pantograph, first determine linear momentum, then force balance condition, and finally the principle dimensions. Because the 2-DOF pantograph does not have the middle link, it is easier to solve the principle dimensions without using the equivalent linear momentum systems (ELMS). For the 3-DOF and 4-DOF principle vector linkages, they have middle links, so the ELMS is used for the middle links which requires a little more effort to calculate the principle dimensions. For the moment balance, first write the angular momentum, and then substitute the position vectors, position vector derivatives, angle relations, and force balance conditions to the angular momentum equation to obtain the final form of the angular momentum; for linear relations of time-dependent parameters, determine the moment balance condition from the angular momentum and subsequently balance solutions; for nonlinear relations of time-dependent parameters, determine the moment balance condition and subsequently balance solutions. Finally perform synthesis of reactionless mechanisms from the principle vector linkages.

The main content of the Fisher's method that Van der Wijk used in his PhD thesis is to calculate the principle dimensions, and by using the auxiliary links/pantograph links to trace the CoM of the whole mechanism. It is shown that the principle vector linkage architecture is force balanced, and for the moment balance, the relative motions of principle vector linkage architecture have to be constrained by additional elements. The moment balance is achieved mainly through the symmetrical design and constraining the DOF of the mechanism, like adding a slider or something to make the DOF of the mechanism reduced to achieve the moment balance. For the grasping mechanism, it is derived from the 4-DOF principle vector linkage with a slider; the motion of the 4-DOF principle vector linkage (grasping mechanism) is reduced in order to achieve the moment balance. Also the bridge and the roof and wall of house can be derived from the 2-DOF principle vector linkage. The above dynamic balanced mechanisms are all synthesized from the principle vector linkages.

In [8], for the dual-V manipulator, it is derived from two balanced pantographs, and by symmetric designing the structure of legs of 4RRR planar parallel manipulator, shaking moment was balanced out each other when moving along the orthogonal axis, so counter-rotations are no longer needed, only counterweights are used, and the disadvantage is that the manipulator is dynamic balanced only when the manipulator moves in the orthogonal axes with non-rotated moving platform. The idea of the above symmetric designing can also be seen as evolving from pantograph arms with a counter-mass (the arm has a parallelogram shape), and the pantograph arms with a counter-mass was evolved from the normal counter-mass adding in each link, as shown in Fig. 1.4. In the similar paper [9], the author derived the

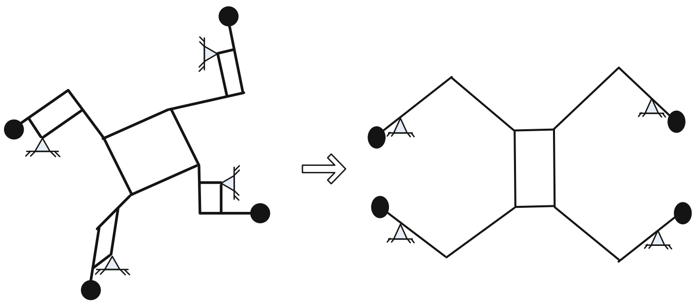

Fig. 1.4 Evolve process for the 4RRR reactionless parallel mechanism

general force balancing conditions of the planar 4RRR parallel manipulator, and the different topologies of 4RRR manipulator from the force balance condition were obtained.

1.3 Balancing at the End of the Design Process

1.3.1 Add Counterweights

1.3.1.1 Normal Counterweights

In [10], a double pendulum was dynamic balanced by using two counterweights and two counter-rotations. The counterweights are placed at the extension of each link like the traditional force balance technique to make the center of mass fixed at revolute joint, and shaking moment balancing is achieved by using planetary gear trains that carry out the counter-rotations. Force balancing condition is derived by using the center of mass formula and making the position of CoM equal to 0; two force balance equations are obtained; from those two static balancing equations it can be seen that the masses and length are both positive; the only way to satisfy the equation is to make the position of the CoM of some links to be negative; to do that, counterweights were added. The shaking moment of upper moving link is balanced by a counter-rotation gear; this counter-rotation gear is mounted on the base, and it is connected to the upper moving link by the following way: there are two gears at base joint (one small gear and one big gear) being fixed together, the counter-rotation gear is connected with the bigger gear, and the small gear is connected to the upper moving link by a belt; through this way, this counter-rotation gear is indirectly connected to the upper moving link and rotates opposite with the upper moving link to achieve the moment balance in order to achieve dynamic balance. For the moment balancing, the author wrote the angular momentum of the whole mechanism, and by making the angular momentum equal to 0, two moment balance equations (moment balance conditions) are derived. The disadvantage of the above force balancing and moment balancing method is that counterweights and planetary gear trains (counter-rotations) are used, which increase the total mass and complexity. In the second part of that paper, the authors also talked about the shaking moment balancing by using flywheel since this solution is constructively more efficient. First the angular momentum of the whole parallel manipulator was derived. In order to achieve shaking moment balance condition for this manipulator, the flywheel was used, and this flywheel needs to have the same and opposite shaking moment so that this flywheel can moment balance the manipulator. This flywheel is driven by another actuator, which belongs to the active dynamic balancing technique. Finally the angular acceleration of this flywheel can be obtained by using the moment formula. But how to link this flywheel to the parallel manipulator was not mentioned.

In [11–13], the idea of dynamic balancing of mechanisms is to use counter-weights and counter-rotations (i.e., geared inertia counterweights and planetary-gear-train-inertia counterweight) to force and moment balance linkages, which is quite straightforward. The center of mass formula was used to derive the center of mass of the whole mechanism; then the center of mass was set to be stationary so that the force balance condition can be obtained; subsequently shaking moment of the linkage was described as the time rate of change of the total angular momentum, and the general formula for the total angular momentum of the linkage was used; after that the total angular momentum was set to 0 in order to derive the dynamic balance condition, but later it was found that it was impossible to achieve dynamic balance unless counter-rotations were added. After adding counter-rotations, set the total angular momentum to 0 and the moment balance condition was obtained. The disadvantage of this balance method is that the planetary-gear-train-inertia counterweight was put on the upper moving link rather than the ground.

In [14], the author derived the 3-DOF parallelepiped mechanism (unit) from the basic 1-DOF pivot link as leg to synthesize the spatial parallel manipulator, but this parallelepiped mechanism requires three counter-rotations and six counterweights to achieve dynamic balance condition, which substantially increased the mass, inertia, and complexity of the mechanism. The above parallelepiped mechanism design is not smart because it used the counterweights and counter-rotations. The dynamic balancing condition was directly derived from the center of mass formula and also set angular momentum to 0. Finally, the parallelepiped mechanism was used to construct the spatial parallel manipulators. How to simplify this mechanism has become a future work.

In [15], a parallelogram 5-bar linkage was proposed as a leg for a planar 3-DOF parallel manipulator. Firstly, the moving platform was replaced by two point masses located at the point of attachment of each of the legs to the moving platform; in order to do that, three conditions have to be satisfied: same mass, same inertia, and same center of mass; secondly, for each leg (includes the replaced mass) the static balancing has to be firstly satisfied in order to achieve the dynamic balancing condition, and for the static balancing, the center of mass equation was used and by making the position of CoM equal to 0, two static balance equations are obtained; after obtaining the equations, the next step is to solve it. From those two static balancing equations it can be seen that the masses and length are both positive; the only way to satisfy the equation is to make the position of the CoM of some links to be negative; to do that, counterweights can be added. For the moment balancing, the author wrote the angular momentum of the 5-bar mechanism, and by making the angular momentum equal to 0, three moment balance equations (moment balance conditions) are derived. From the static balancing, two equations were derived, and from the dynamic balancing (angular momentum condition), another three equations were derived; that is, five equations were provided for the dynamic balancing of the leg (5-bar linkage). The novelty of this paper is that the authors proposed the parallelogram 5-bar linkage as a leg of a planar 3-DOF parallel manipulator and analyzed the dynamic balancing of the leg. Future wok is that employ the proposed leg for other kinds of spatial parallel manipulators. The above method is based on the decomposition and integration method; that is, propose a single linkage (leg) first, then dynamic balancing a single linkage, and finally combine those linkages to form the whole parallel manipulator; in other words, decompose first and integrate later. But the disadvantage of the above reactionless mechanism is that the counterweights and counter-rotations were used, which increased the weight, inertia, and complexity. The counterweights are used to keep constant the position of the center of mass while the counter-rotations are used to keep constant the angular momentum.

In [16], the idea of putting the gear, which is used for balancing the shaking moment, on the base can lead to smaller increase of moving masses. This gear is originally mounted on the moving link, so the mass of the counterweight of the base link is needed to force balance this gear as well, but if the gear is put on the mechanism frame, then the counterweight of the base link does not need to force balance this gear, which means the mass of this counterweight of the base link can be decreased. But the disadvantage is that the number of extra devices increased. The balancing method above in which the gear was put on the base of the mechanism is an extension of the method in [11–13].

1.3.1.2 Add CRCM

In [17], it presented the shift modification rules, and the counter-rotary counterweight was evolved from this shift modification rules. In [18], the CRCM was proposed and compared with the separate counter-rotation, and it came to the conclusion that the CRCM principle has reached reduction of added mass and added inertia.

In [19], another three CRCM-based balancing principles were derived, i.e., low inertia configuration balancing principle, one CRCM balancing principle, and only CRCMs near the base balancing principle. According to the paper, the advantage of the first new balancing principle is its low inertia, the advantage of the second new balancing principle is that only one CRCM is necessary for the moment balance of the complete mechanism, and the advantage of the third new balancing principle is its compact construction. Finally several CRCM-based 2-DOF parallel mechanisms were synthesized by using the CRCM-balanced double pendulum. And the 3-DOF planer and spatial parallel manipulators are synthesized by using the balanced double pendulum.

Our perspective is that for the one CRCM configuration, it is not a smart balancing principle because there are two gears on the upper moving link rather than the base frame. For the only CRCMs near the base configuration, the principle is roughly the same with the idler loop or the V. Arakelian and M. Smith mechanism in [10, 16]; that is, the moment of upper moving link is balanced by a CRCM which is connected to the upper moving link through a gear/belt transmission, and the moment of base link is balanced by another CRCM which is connected to a gear that is attached to the base link. But the disadvantage of the only CRCMs near the base configuration is that the CRCM that is used for moment balancing the upper moving link is on the base link, which makes the system heavier. The V. Arakelian and M. Smith mechanism in [10, 16] is that the gear that is used for moment balancing the upper moving link is on the base/ground, which does not affect the system at all.

In [20], the total mass (increase) and reduced inertia of double pendulum were compared within the counter-rotary counter-mass (CRCM), separate counter-rotations (SCR), duplicate mechanisms (DM), and idler loop. Firstly the reduced inertia and total mass of these four balancing principles were derived, and mass-inertia factor was established and this factor was used for judging the additional mass and additional inertia. The comparison results showed that the DM principle had the lowest values for the mass-inertia factor, which means that the DM principle is the most advantageous for low mass and low inertia dynamic balancing, but DM principle requires a larger space. CMCR principle is the second lowest values for the mass-inertia factor, which means CRCM principle is the second most advantageous for low mass and low inertia dynamic balancing, and CRCM principle does not require larger space compared with the DM principle, so the CRCM has more potential to use. The general procedure of the above analysis can be concluded as follows: Step 1: The position vectors of the counter-masses and lump mass were obtained first; then with the derivative of those position vectors, the linear momentum was derived by using linear momentum formula and subsequently making the linear momentum equal to 0, and the force balancing condition was derived. Step 2: The angular momentum about reference point was obtained by using the angular momentum formula, and the relations between the gears were applied to simplify the angular momentum, by making the angular momentum equal to 0; the moment balancing (dynamic balancing) condition was derived. Step 3: When deriving the reduced inertia, either we can determine the kinetic energy first and derive the reduced inertia, or directly obtain the reduced inertia by copying the coefficients of angular velocities in the angular momentum formula but with the transmission ratios squared. Step 4: Determine the total mass. Step 5: The total mass and reduced inertia are compared among those four balancing principles.

Our thought is that it is not necessary to compare the total mass and inertia, because some of the masses and inertia are on the ground, not on the mechanism, so those masses that are on the ground do not really affect the system. In [21] it is the same with the above paper except it compared the total mass and reduced inertia among SCR, CRCM, and DM for a 1-DOF rotatable link rather than a double pendulum.

1.3.1.3 Add Assur Group

In [22], the author used the Assur group and three counterweights to achieve dynamic balance; three counterweights are used to achieve force balance, and Assur group and the counterweights are used to achieve the moment balance. In [23], the paper talked about the shaking force balancing and shaking moment balancing for a planar 3RPR parallel manipulator with prismatic joints; the author proposed two methods for the balancing: the first one is based on the addition of an idler loop between the moving platform and the base; it uses lots of counterweights and counter-rotations, which substantially increase the mass and inertia. The second method is based on the addition of a Scott-Russell mechanism (i.e., special crank-slider mechanism, which belongs to the Assur group) to each leg of the 3RPR parallel manipulator, which can decrease the number of counter-rotations. The second method which is based on the addition of a Scott-Russell mechanism belongs to the passive dynamic balancing; it requires three counter-rotations. It is expected that if we change the passive balancing to active balancing, then the number of counter-rotations can be reduced.

1.3.1.4 Add Active Driven CRCM

In [24], by active driving the CRCM, the double pendulum can be dynamic balanced. The specific angular momentum of ACRCM was derived from the derived angular momentum, then the rotational velocity of the ACRCM was obtained, and the torque of the actuator that actively drove the ACRCM was obtained. Through evaluation, the author found that the ACRCM principle is better than the passive CRCM or with separate counter-rotations mainly in terms of total mass-inertia relation. A 2-DOF ACRCM-balanced parallel manipulator was derived by combining two CRCM to one ACRCM as shown in Fig. 1.5. The 3-DOF planer and spatial parallel manipulators were synthesized by using the ACRCM-balanced double pendulum. For the planer parallel manipulator, it has 1-DOF rotation within a single plane, so only one ACRCM can be used to balance the complete mechanism. For the spatial 3-DOF parallel manipulator, the rotations of the moving platform and links are in two planes; therefore two ACRCM are used to balance the mechanism. It uses the ACRCM; the whole system will still become heavier, because it uses the ACRCM; it belongs to the "consider at the end of the design process" approach.

In the above paper, a 2-DOF ACRCM-balanced parallel manipulator was derived by combining two CRCM to one ACRCM as shown in Fig. 1.5. Inspired by the above design, new 3-DOF planar 3-2RRR and 4-2RRR reactionless parallel manipulators and spatial 3-DOF 3-2RRR and 4-2RRR reactionless parallel manipulators are derived as shown in Fig. 1.6 by employing 2-DOF ACRCM-balanced mechanism.

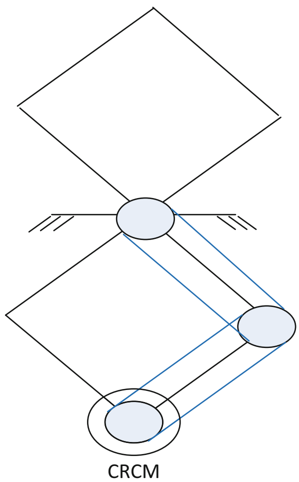

Fig. 1.5 ACRCM-balanced manipulator

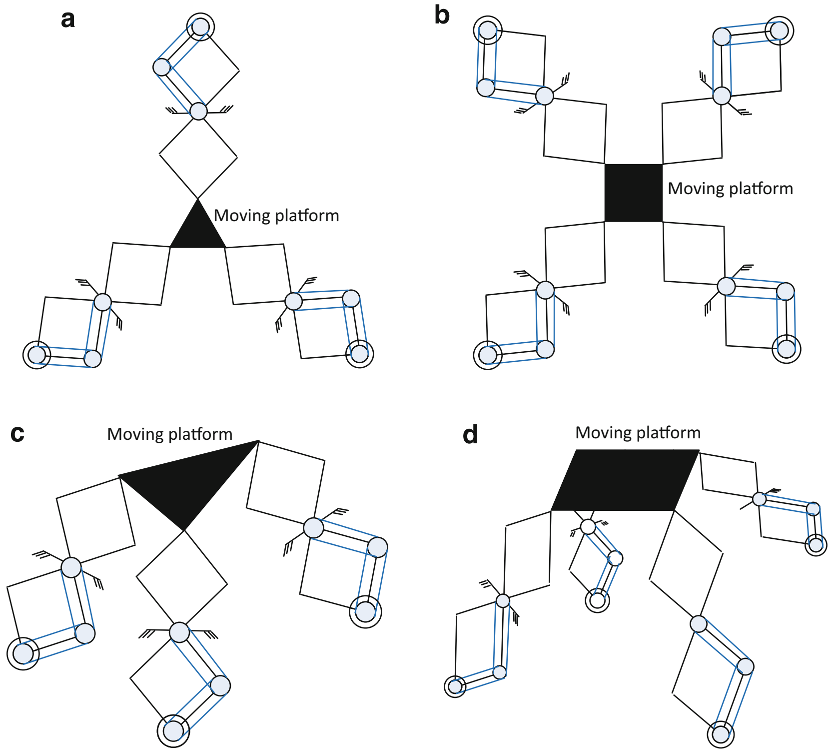

Fig. 1.6 3-DOF planar: (**a**) 3-2RRR and (**b**) 4-2RRR and spatial (**c**) 3-2RRR and (**d**) 4-2RRR reactionless parallel manipulators

1.3.2 Add Auxiliary Links

For dynamic balancing of Clavel's Delta robot, in [2], for the force balance, a solution is proposed that each leg and one-third of the moving platform mass together are balanced with one counter-mass plus an additional link; that is, each leg becomes a 3D pantograph. Furthermore, due to the fact that the moving platform of the Delta robot does not rotate, the above force balance method can be simplified to the following: one leg being a 3D pantograph can balance the complete mass of the moving platform and part of the mass of the links that are attached to the moving platform of the other two legs, and two other counter-masses are attached to the other two legs; that is, the complete Delta robot is force balanced by three counter-masses and additional link. For the moment balance, the author used the active driven method because the angular momentum of the force balanced Delta robot is dependent on the velocity of mechanism; it cannot be made constant by using passive moment balancing methods, for example, geared counter-rotating inertias. It is found that the mass of additional link can be used to force balance all the mass of the moving platform and part of the mass of the links attached to the moving platform of legs 2 and 3. Fisher's method can also be seen as the method of addition of auxiliary links.

1.3.3 Through Reconfiguration

Here force balancing through reconfiguration concept is proposed; for example, we can use screw link as link, the link can be moved so that the CoM of the link can be moved to the revolute joint point, and then it is forced balanced; in this method, counterweight is not used but through reconfiguration of the system by moving the screw link, the system will not become heavy. Figure 1.7 shows such a concept of force balancing through reconfiguration.

The purpose of using counterweight is to move the CoM to the still point, so the question is that can we not use counterweight to achieve the same goal. We can reconfigure the link so that CoM is moved to the still point. We just want to use the function of their links, and in this case it is the rotational function.

For the three link case, if we use counterweights, then it becomes much heavier (Fig. 1.8).

From above, we can see that the function (i.e., rotational function of the links) is not changed at all; the function is still remained. For the force balance by adding counterweight, the whole system becomes much heavier. For the 4R 4-bar linkage, we have the following if the 4R 4-bar linkage is regarded as an open chain of three links in series (Fig. 1.9):

For the crank-slider mechanism, it can be seen as an open chain of three links in series; the third link is a slider that does not rotate and it solely translates. Because link 3 does not rotate, the CoM of the link 3 can be in any point in link 3 (Fig. 1.10).

The above force balanced through reconfiguration crank-slider mechanism maybe can be used as Scott-Russell mechanism, and use the force balanced through reconfiguration crank-slider mechanism to synthesize the planar 3RPR parallel

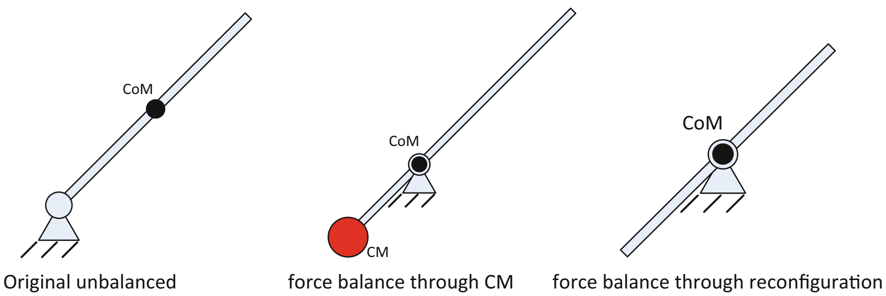

Fig. 1.7 Concept of force balancing through reconfiguration

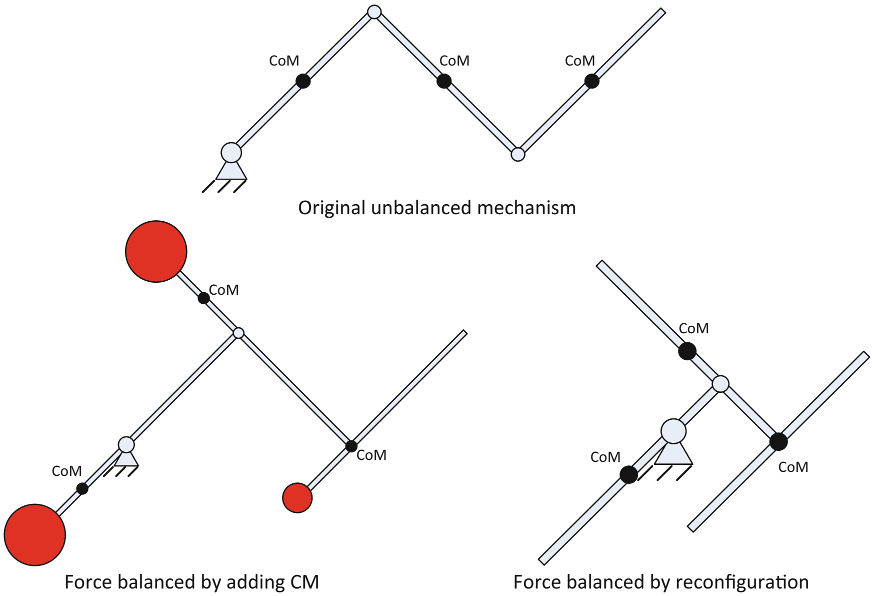

Fig. 1.8 Force balancing of 3-DOF serially connected link through reconfiguration

manipulator. One can see that force balance through reconfiguration does not add any counterweights, and also the function of the crank-slider mechanism remains the same, and does not change at all. If the links of the above crank-slider mechanism have same length, then it is moment balanced as well because it is symmetrical design [8].

In [23], we can use the above force balance through reconfiguration crank-slider mechanism as a Scott-Russell mechanism instead of traditional Scott-Russell mechanism (i.e., an Assur group) and add it in each leg of the 3RPR planar parallel manipulator as shown in Fig. 1.11. And also it is expected that if we change the passive balancing to active balancing, then the number of counter-rotations can be reduced to only one counter-rotation.

Only six counterweights and three counter-rotations are used if it is passive balancing. One can see that by using the force balance through reconfiguration crank-slider mechanism as a Scott-Russell mechanism (i.e., an Assur group), no counterweight is added on the Scott-Russell mechanism; if we stick to the original/traditional Scott-Russell mechanism, two counterweights are added on the Scott-Russell mechanism, which increases the weight. Based on the extension of [22], we can use reconfiguration method to force balance these 4-bar linkage with Assur group instead of adding those three counterweights, and use these through reconfiguration dynamic balanced 4-bar linkage with Assur group to construct the whole parallel robot; that is, decompose first and integrate later. But in [22], what makes the author think to add three CM to those positions to achieve force balance is not explained.

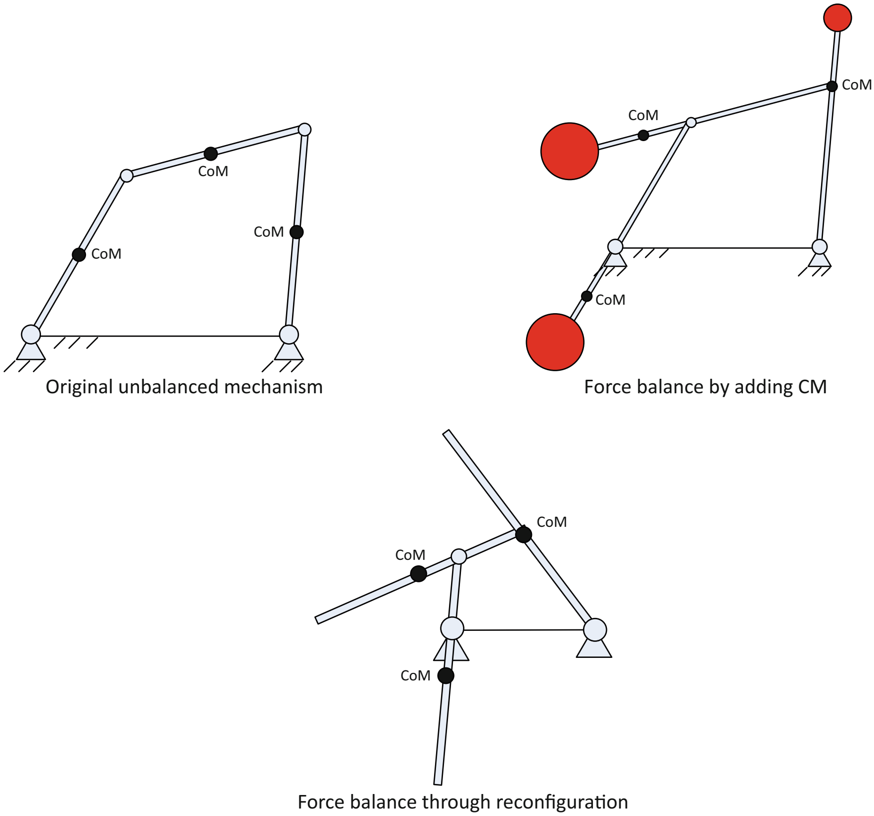

Fig. 1.9 Force balancing of 4R 4-bar linkage through reconfiguration (case I)

The above illustrates the dynamic balancing through reconfiguration method; instead of adding CM, the purpose of which is to move CoM, we can use reconfiguration method to achieve the same goal.

For the SteadiCam, it uses counterweights to achieve force balance, and through adjusting those mass relations dynamic balance is achieved. Here the concept of mass relationship is proposed. There are two links in the bottom acting as the counterweights; it is force balanced. Now if we spin it, it is dynamic balanced. If we move the link 2 up as shown in Fig. 1.12, it is still force balanced, but not dynamic balanced any more. So the question is how we can rearrange the structure, i.e., reconfigure the structure, to regain the dynamic balance.

Imagine that we move an extreme case; that is, let's move the link 2 all the way to the top; it is obvious that if we want to regain the dynamic balance, we need to move the camera counterclockwise direction, so does the mass 1. So we get the same situation; it is just that two masses are in the top and one mass is in the bottom. In other words, if we move the link 2 up a bit, i.e., counterclockwise direction, we need to move the camera counterclockwise as well and so does the mass 1 in order

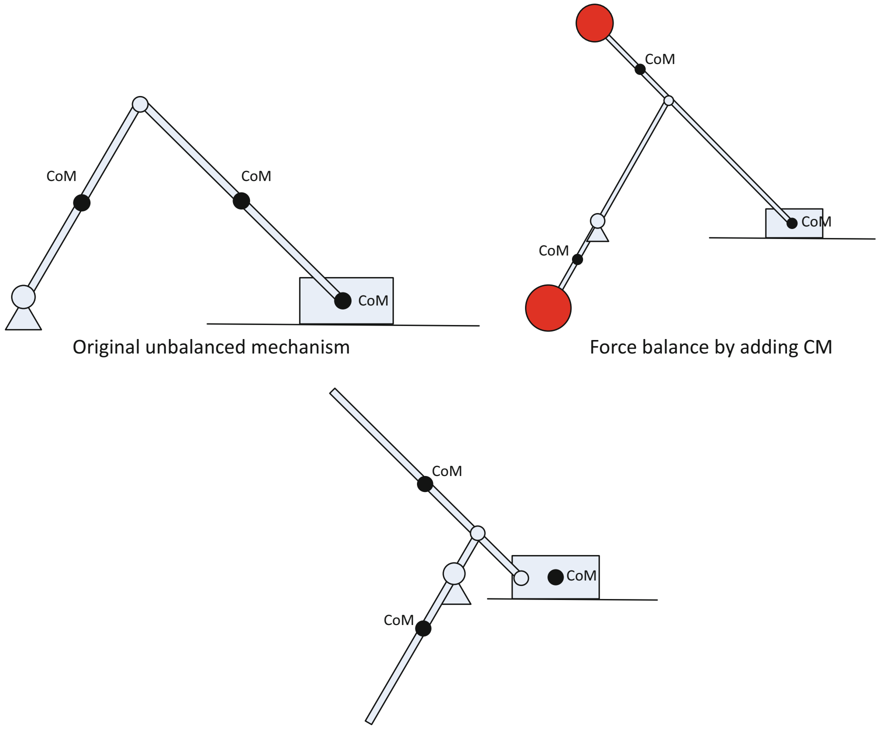

Fig. 1.10 Force balance of crank-slider mechanism through reconfiguration (if the links have same length, it is moment balanced as well)

to regain the dynamic balance. It is all about mass relations; as long as we keep those mass relations, the dynamic balance can be achieved. What is important is the relationship of these three masses.

Figure 1.13 can also be seen as the dynamic balancing through reconfiguration, i.e., through moving the link 2 and mass 2 to achieve dynamic balancing, adapting the position of the link 2 and mass 2.

1.3.4 Active Dynamic Balancing Unit

In [25], the paper deals with the active dynamic balancing. The paper presented an active dynamic balancing unit (ADBU), which is a unit that can be mounted on the base of the unbalanced mechanism and the unit is controlled such that the complete system is dynamically balanced. The goal of the ADBU is to produce balancing forces and balancing moments that are equal and opposite to the total

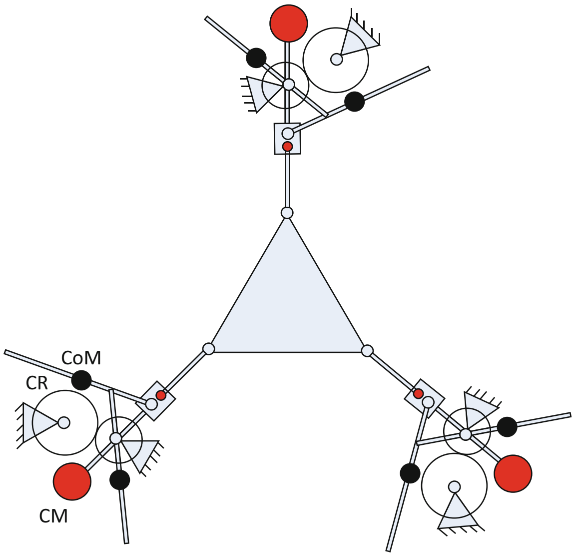

Fig. 1.11 Dynamic balanced 3RPR planar parallel manipulator (passive balancing)

shaking forces and total shaking moments of the machine. The ADBU constitutes of three counter-masses and three counter-rotations; the three counter-masses are used to force balance the shaking force along *x*, *y*, and *z* directions and the three counter-rotations are used to moment balance the shaking moment about *x*, *y*, and *z* directions. Consider the low mass addition aspect; the ADBU is evolved to a new ADBU that the three counter-masses and three counter-rotations are combined. In that paper, the ADBU needs to balance an *xy*-robot, which means this robot has two shaking forces in the plane, i.e., *x* and *y* directions and one shaking moment about *z* direction, so the ADBU only needs to balance two shaking forces in *x* and *y* directions and one shaking moment in *z* direction. So the ADBU is reduced from the original one to the one that has only two translation motions and one rotation motion. A 2RRR parallel mechanism is used to move the disc in *x* and *y* directions; the disc can also rotate; that is, this disc is a CRCM. Future work is to find advanced control strategies for controlling the ADBU.

In [26], a 3-DOF active dynamic balancing mechanism (ADBM) which is attached to the moving platform was proposed, and it is similar to the ADBU. This mechanism not only can balance the moving platform, but also can actuate the moving platform to move in a certain trajectory, but the main function of the ADBM is to balance the shaking force and shaking moment of the moving platform. The counterforces and counter-moments produced by ADBM are equal to the shaking forces and shaking moments plus the actuated force and actuated moment (i.e., one part of the forces and moments produced by ADBM is used to balance the shaking force and shaking moment, the other part of the forces and moments produced by ADBM is used to actuate the moving platform to a certain trajectory).