Force Balance of Mechanisms and Parallel Robots Through Reconfiguration Method

Dan Zhang and Bin Wei

Abstract When mechanisms and parallel robots move, because the center of mass (CoM) is not fixed, vibration is produced in the system. Normally, force balance is achieved by using counterweights or damping methods. However, the problem is that the whole system will become heavier and have more inertia. Here we try to achieve force balance not by using counterweights or damping, but through designing naturally force balanced mechanisms to achieve the goal, this can be done by the new method we proposed here, i.e. force balancing through reconfiguration, which can reduce the addition of mass and inertia of the whole system. After designing a naturally force balanced single leg, legs will be combined to synthesize parallel mechanisms. This research is important for manufacturing and space areas.

Keywords Force balance · Reconfiguration · Counterweight · Mechanism · Parallel robots

1 Introduction

Force balancing for mechanisms has become an important part of mechanism design and development. When mechanisms and parallel robots move, because the center of mass is not fixed, vibration is usually produced in the system, which greatly deteriorates the accuracy performance. Shaking force balancing can be achieved by making the center of mass of mechanism be fixed. Parallel mechanisms have been widely used in many areas, but a problem occurs when parallel manipulators are in operations, it is not force balanced, which greatly deteriorate the

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performance of parallel manipulators. How to force balance these parallel manipulators has become an issue for many scholars and industries. Traditionally, counterweights (CM) are usually used to achieve force balance, i.e. make the center of mass fixed, for example, at the rotation joint. Balance is all about using extra devices to counter-balance the shaking force that the original mechanism exerted to the base. But a problem occurs when using those counter-balancing devices, i.e. the whole mechanisms will become heavier and therefore lead to more inertia. How to design reactionless mechanisms with minimum increase of mass and inertia has become a common desire. There are generally two main ways for balancing, i.e. balancing before kinematic synthesis and balancing at the end of the design process as shown in Fig. 1. For the balancing before kinematic synthesis, Fisher's method is a typical example of this. Recently Wijk has thoroughly investigated this method in his PhD thesis [1] and in [2], for the shaking force balance, first to determine the linear momentum, then determine the force balance condition and finally to determine the principle dimensions. Finally synthesize reactionless mechanisms from the principal vector linkages. In [3, 4], for the Dual-V manipulator, four counterweights are added to the revolute joints to achieve the force balance. In [5], a four-bar linkage was proposed as building unit to synthesize planar and spatial 3-DOF 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.

Under the category of balancing at the end of the design process, add CM, add active dynamic balancing unit (ADBU) and add auxiliary links are mostly used principles. In [6], a parallelogram five-bar linkage was proposed as leg for planar 3-DOF parallel manipulator. Two force balance equations are obtained, and it is found that the only way to satisfy the equation is to make the position of the CoM of some links to be negative, to do that, CM can be added. In [7–9], the idea of force balancing of mechanisms is to use CM. The disadvantage of this balance method is that the CM was put on the upper moving link rather than the ground. In [10], a dyad was force balanced by using two CMs. The CM is placed at the extension of each link to make the CoM fixed at joint, force balancing condition was derived by adding CM same as in [11]. The disadvantage of the above method is that CM

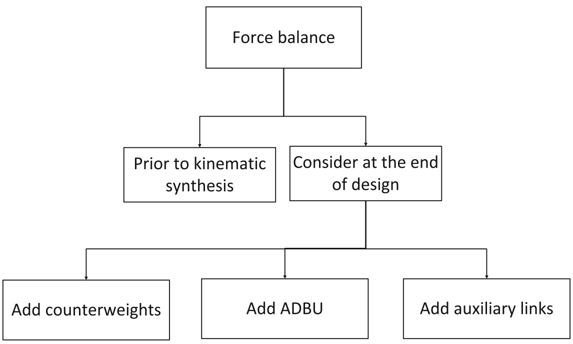

Fig. 1 Two main categories for force balancing

increases the weight and complexity of the whole system. In [12], the author derived the 3-DOF parallelepiped mechanism from the basic 1-DOF pivot link as leg to synthesize the spatial parallel manipulator, but this parallelepiped requires six CMs to achieve force balance, which substantially increased the mass and inertia. In [13], the method of addition of an idler loop between the moving platform and the base is proposed for balancing a planar 3-RPR parallel manipulator with prismatic joints, it uses lots of CMs, which substantially increase the mass. In [14, 15], the CRCM was proposed, and it came to conclusion that the CRCM principle has reached reduction of added mass and inertia. In [16, 17], the total mass and reduced inertia of pendulum were compared within the CRCM, duplicate mechanisms and idler loop. The mass-inertia factor was established for judging the additional mass and additional inertia. The comparison results showed that DM principle is the most advantageous for low mass and inertia balancing, but DM principle requires a larger space. CMCR principle is the second lowest values for mass-inertia factor, and CRCM principle does not require larger space, so the CRCM have more potential to use. In [18], by active driving the CRCM, the double pendulum can be force balanced. Through evaluation, it is found the ACRCM principle is better than passive CRCM in terms of total mass-inertia relation.

In this paper we will propose a new force balancing concept, i.e. force balance through reconfiguration, the advantage of which is that addition of CM can be reduced. For the shaking force balancing, for example, when a link is rotating around a pivot, because the CoM of the link is not still, so the link will have a shaking force, which makes it vibrate. When a counterweight is added, for example, to the extended part of that link, the CoM of the whole link is fixed to that revolute joint, then it is force balanced, thus the vibration is eliminated. If we add the counterweight, the system will become heavy, that is the drawback of using CM. The purpose of using a counterweight is to move the CoM to the still point. The question is whether it is possible to achieve the same goal by not using a counterweight. This is in fact possible, so for example, a screw link can be used and moved to the point where the CoM moves to the still point, and it is then force balanced. In this method, a counterweight is not used but, through reconfiguration of the system by moving the screw link, the system will not become heavy. Based on this idea, we will first dynamically balance a single leg by the reconfiguration method (decomposition) and then combine the balanced legs to synthesize the whole parallel mechanism (integration); i.e. the decomposition and integration concept.

2 Force Balance 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 still point, then it is forced balanced, in this method, CM is not used but through reconfiguration, the system will not become heavy. The Fig. 2 shows such a concept of force balancing through reconfiguration.

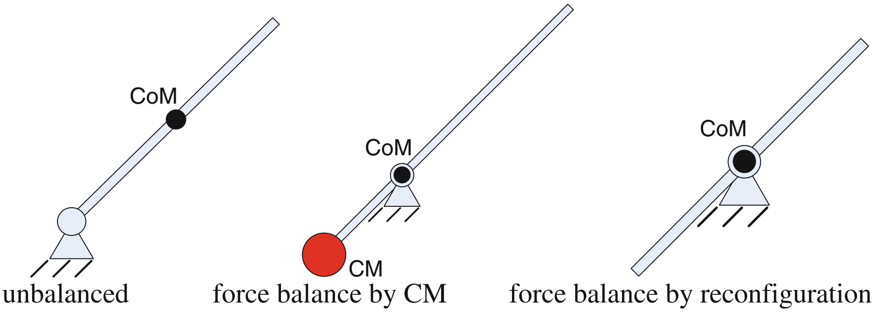

Fig. 2 Concept of force balancing through reconfiguration

The purpose of using CM is to move the CoM to the still point, so the question is that can we not use CM 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. Now for the two link scenario, we have the force balancing of 2-DOF serially connected link through as shown in Fig. 3.

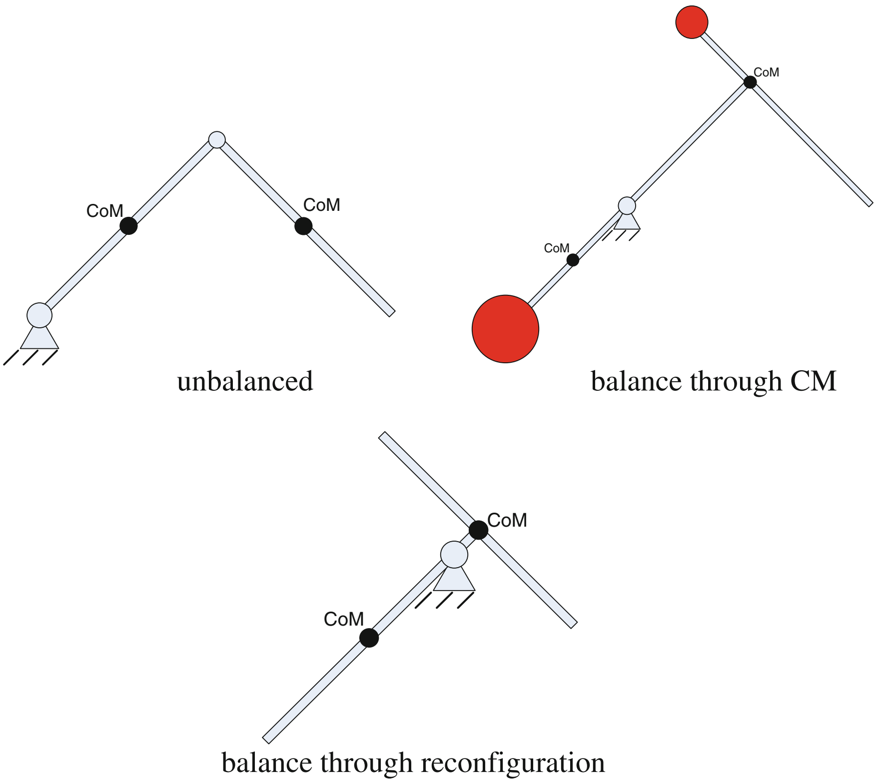

Fig. 3 Force balancing of 2-DOF serially connected link through reconfiguration

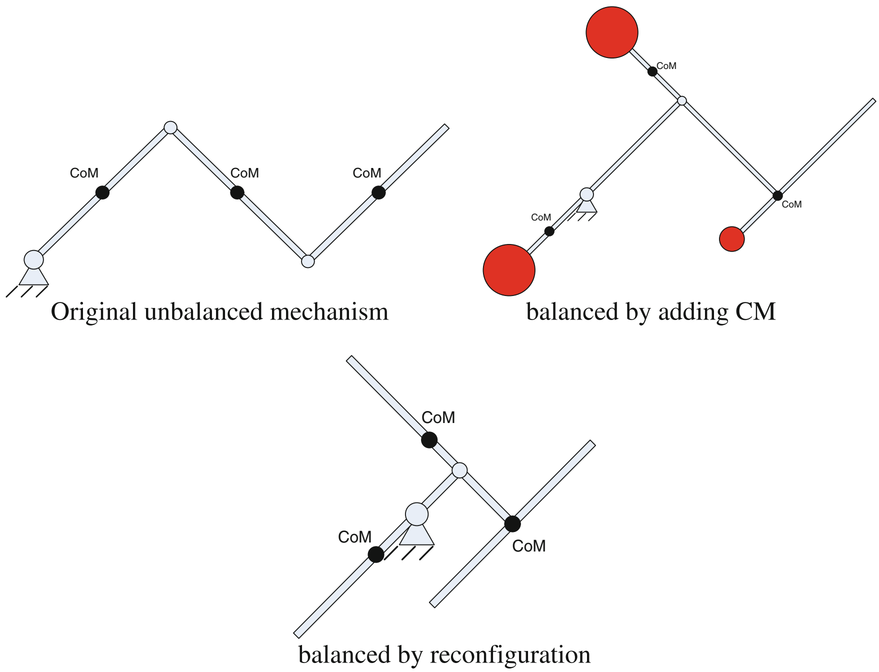

Fig. 4 Force balancing of 3-DOF mechanism through reconfiguration

From Fig. 3, we can see that force balance through reconfiguration does not add any CM, whereas for the force balance by adding CM, the whole system becomes heavier. For the three link case, if we use CM, then it becomes much heavier.

From Fig. 4, we can see that rotational function of the links is remained. For the 4R four bar linkage, we have the results as in Fig. 5 if the 4R four-bar linkage is regarded as an open chain of three links in series.

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, so the CoM of the link 3 can be in any point in link 3.

The force balanced through reconfiguration crank-slider mechanism shown in Fig. 6 can be used as Scott-Russel mechanism, and use the force balanced through reconfiguration crank-slider mechanism to synthesize the planar 3-RPR parallel manipulator. One can see that force balance through reconfiguration does not add any CM, and also the function of the crank-slider mechanism remains the same. If the links of the above crank-slider mechanism have same length, then it is moment balanced as well because it is symmetrical design [3].

Based on the decomposition and integration idea that we will first dynamically balance a single leg by the reconfiguration method and then combine the balanced legs to synthesize the whole parallel mechanism, in [13], we can use the above

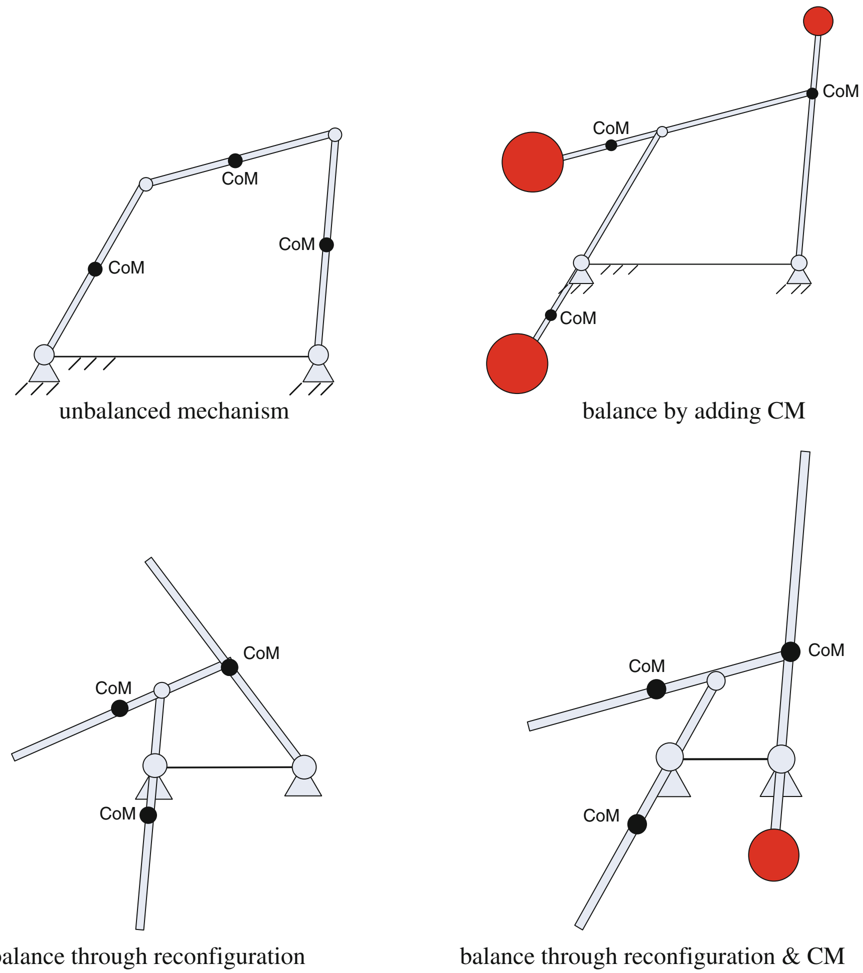

Fig. 5 Force balancing of 4R four-bar linkage through reconfiguration

force balance through reconfiguration crank-slider mechanism as a Scott-Russell mechanism instead of traditional Scott-Russell mechanism and add it in each leg of the 3-RPR planar parallel manipulator as shown in Fig. 7.

One can see that by using the force balance through reconfiguration crank-slider mechanism as Scott-Russell mechanism, no CM is added on the Scott-Russell mechanism. Based on the extension of [19], we can use reconfiguration method to force balance these 4-bar linkage with Assur group instead of adding three CM, and use these through reconfiguration force balanced 4-bar linkage with Assur group to construct the whole parallel robot, i.e. decompose first and integrate later.

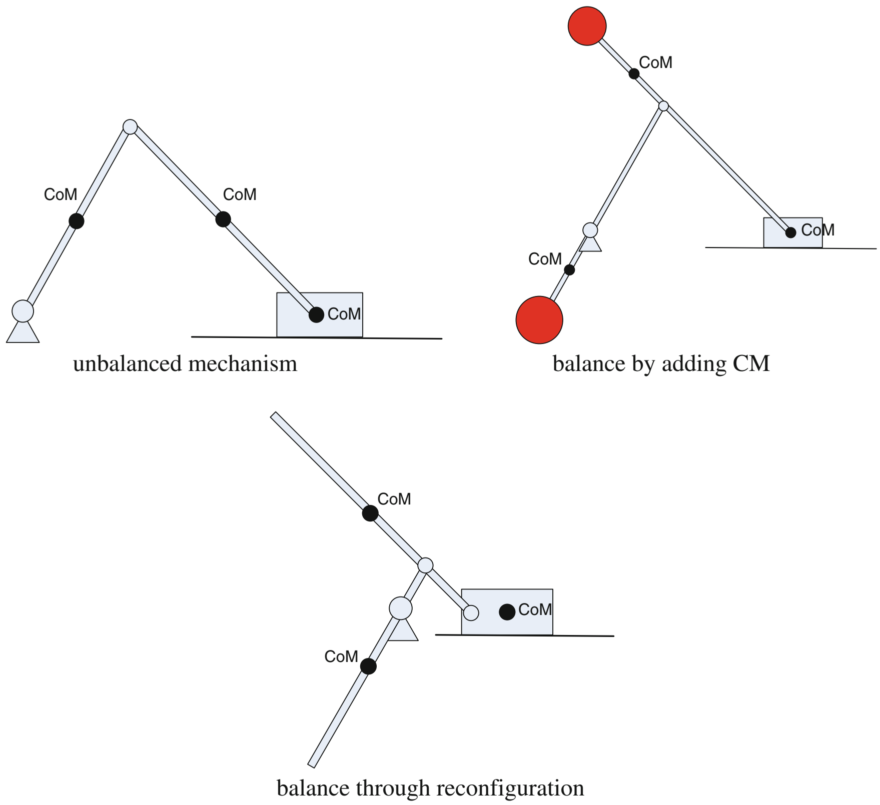

Fig. 6 Force balance of crank-slider mechanism through reconfiguration

For the delta robot, if each leg is regarded as a three-link open chain (please note that the third link is the moving platform that only can do translation motions, so the CoM of the moving platform can be located in any point in the moving platform), we can have the result as shown in Fig. 8.

Figure 8 illustrates the dynamic balancing through reconfiguration method, stead of adding CM, the purpose of which is to move CoM, we use reconfiguration method to move the CoM.

For the SteadiCam, it uses CM to achieve force balance, and through adjusting those mass relations to achieve dynamic balance. Here the concept of mass relationship is proposed. There are two links in the bottom acting as the CM, it is force balanced. Now if we spin it, it is dynamic balanced. If we move the link 2 up as shown in Fig. 9, 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.

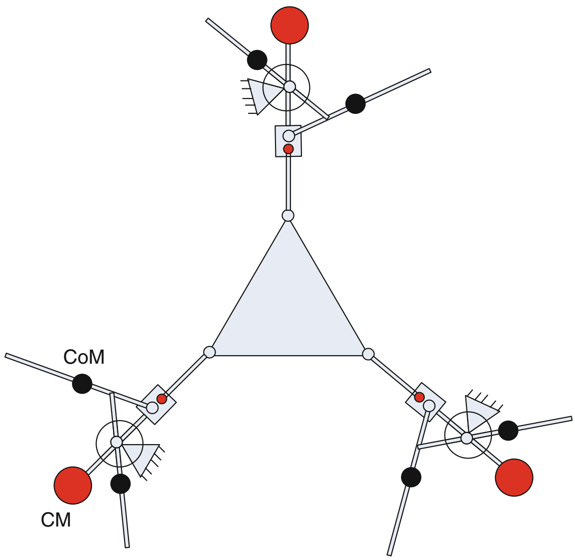

Fig. 7 Force balanced 3RPR planar parallel manipulator

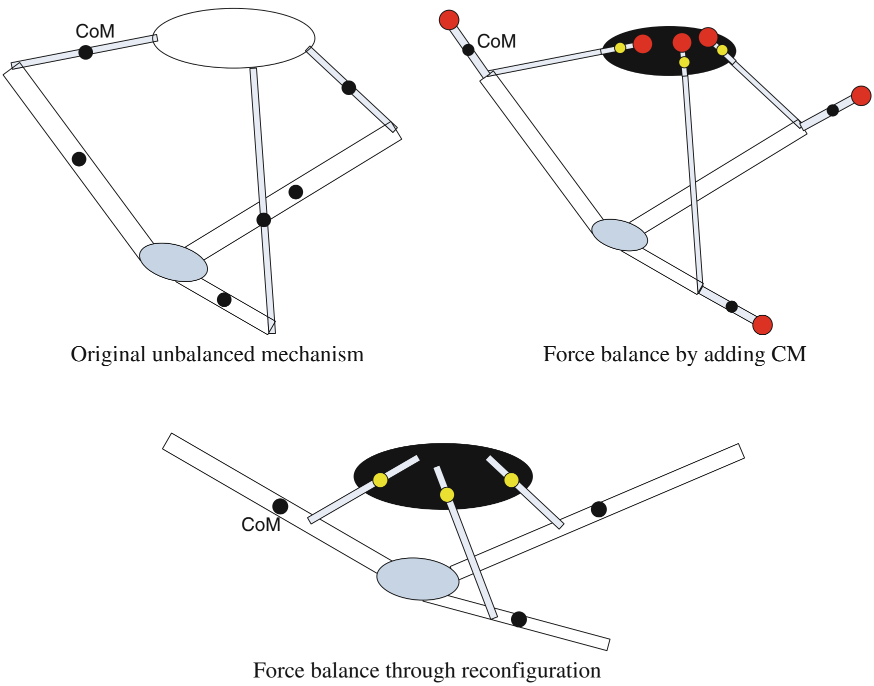

Fig. 8 Force balanced delta robot

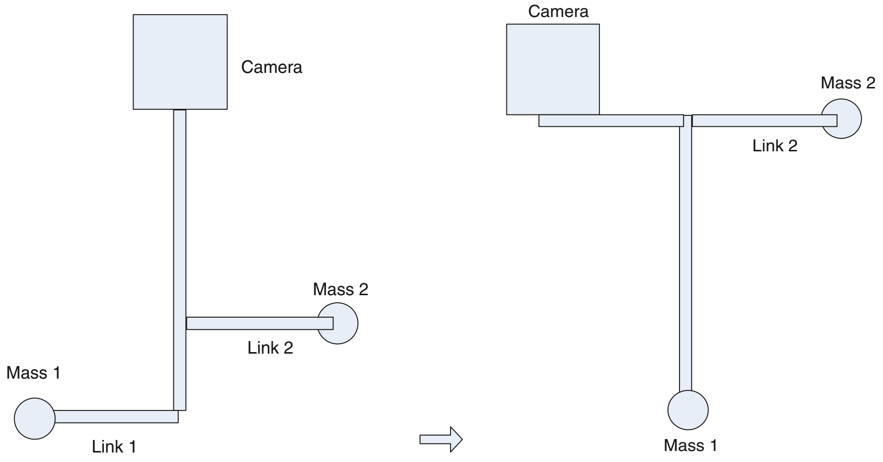

Fig. 9 Simplified version of SteadiCam

Imagine that we move an extreme case, i.e. move 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 counter-clockwise direction, so does the mass 1. It is all about mass relations, as long as we keep those mass relations, the dynamic balance can be achieved.

Figure 10 can also be seen as the dynamic balancing through reconfiguration, i.e. through moving the link 2 & mass 2 to achieve dynamic balancing, adapting the position of the link 2 & mass 2.

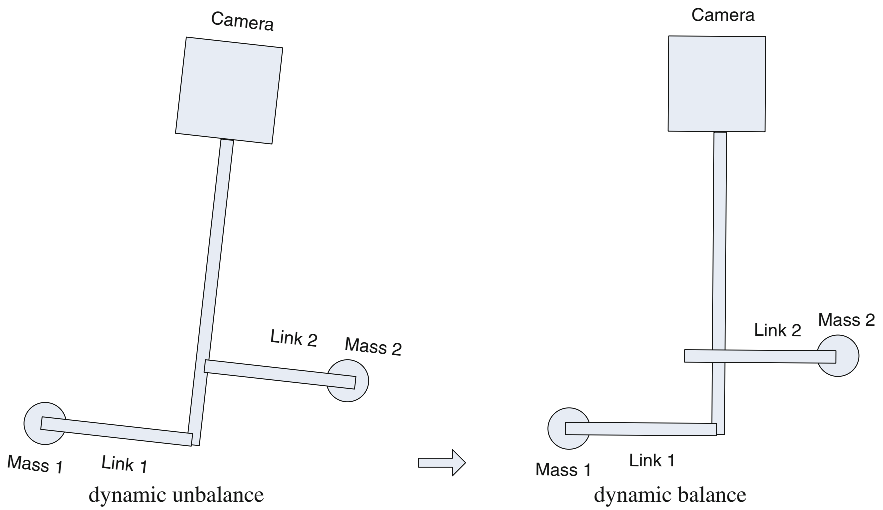

Fig. 10 Dynamic unbalance and balance of SteadiCam

3 Conclusion

In this paper, the concept of force balancing through reconfiguration is proposed, which can reduce the addition of mass and inertia of the system. After designing a force balanced single leg, legs will be combined to synthesize parallel mechanisms based on decomposition and integration concept to synthesize parallel mechanisms to improve the overall performance of parallel robots.

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References

1. Wijk, V.: Methodology for analysis and synthesis of inherently force and moment-balanced mechanisms—theory and applications. Ph.D. dissertation, University of Twente, Netherlands (2004)
2. Wijk, V., Herder, J.: Synthesis method for linkages with center of mass at invariant link point-Pantograph based mechanisms. Mech. Mach. Theory **48**, 15–28 (2012)
3. Wijk, V., Krut, S., Pierrot, F., Herder, J.L.: Design and experimental evaluation of a dynamically balanced redundant planar 4-RRR parallel manipulator. Int. J. Robot. Res. **32**, 744–759 (2013)
4. Wijk, V., Krut, S., Pierrot, F., Herder, J.L.: Generic method for deriving the general shaking force balance conditions of parallel manipulators with application to a redundant planar 4-RRR parallel manipulator, IFToMM 2011 World Congress: In: The 13th World Congress in Mechanism and Machine Science, Mexico, pp. 1–9 (2011)
5. Gosselin, C., Vollmer, F., Cote, G., Wu, Y.N.: Synthesis and design of reactionless three-degree of freedom parallel mechanisms. IEEE Trans. Robot. Autom. **20**(2), 191–199 (2004)
6. Foucault, S., Gosselin, C.: Synthesis, design, and prototyping of a planar three degree-of-freedom reactionless parallel mechanism. J. Mech. Des. Trans. ASME **126**(6), 992–999 (2005)
7. Gao, F.: Complete shaking force and shaking moment balancing of four types of six-bar linkages. Mech. Mach. Theory **24**(4), 275–287 (1989)
8. Gao, F.: Complete shaking force and shaking moment balancing of 26 types of four-, five- and six-bar linkages with prismatic pairs. Mech. Mach. Theory **25**(2), 183–192 (1990)
9. Gao, F.: Complete shaking force and shaking moment balancing of 17 types of eight-bar linkages only with revolute pairs. Mech. Mach. Theory **26**(2), 197–206 (1991)
10. Arakelian, V.H., Smith, M.R.: Design of planar 3-DOF 3-RRR reactionless parallel manipulators. Mechatronics **18**(10), 601–606 (2008)
11. Foucault, S., Gosselin, C.: Synthesis, design, and prototyping of a planar three degree-of-freedom reactionless parallel mechanism. J. Mech. Des. Trans. ASME **126**(6), 992–999 (2005)
12. Wu, Y.N., Gosselin, C.: Design of reactionless 3-DOF and 6-DOF parallel manipulators using parallelepiped mechanisms. IEEE Trans. Rob. **21**(5), 821–833 (2005)
13. Briot, S., Bonev, I.A., Gosselin, C.M., Arakelian, V.: Complete shaking force and shaking moment balancing of planar parallel manipulators with prismatic pairs. In: Proceedings of the Institution of Mechanical Engineers—Part K, vol. 223, no. 1, pp. 43–52 (2009)

14. Herder, J.L., Gosselin, C.: A counter-rotary counterweight (CRCM) for light-weight dynamic balancing. In: Proceedings of DETC 2004 ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference, USA, pp. 1–9 (2004)
15. Herder, J.: Reaction-free Systems. Principles, conception and design of dynamically balanced mechanisms. Technical Report, Laval University (2003)
16. Wijk, V., Demeulenaere, B., Herder, J.L.: Comparison of various dynamic balancing principles regarding additional mass and additional inertia. ASME J. Mech. Robot. **1**(4), 041006-1-9 (2009)
17. Wijk, V., Demeulenaere, B., Gosselin, C., Herder, J.L.: Comparative analysis for low-mass and low-inertia dynamic balancing of mechanisms. ASME J. Mech. Robot. **4**(3), 031008-1-8 (2012)
18. Wijk, V., Herder, J.L.: Dynamic balancing of mechanisms by using an actively driven counter-rotary counter-mass for low mass and low inertia. In: Proceedings of the Second International Workshop on Fundamental Issues and Future Research Directions for Parallel Mechanisms and Manipulators, France, pp. 241–251 (2008)
19. Briot, S., Arakelian, V.: Complete shaking force and shaking moment balancing of in-line four-bar linkages by adding a class-two RRR or RRP Assur group. Mech. Mach. Theory **57**, 13–26 (2012)