Development of Double Parallelogram Flexure Mechanism via Assembly Route

Prasanna S Gandhi, Kaustubh Sonawale, Vaibhav Soni

Abstract

Flexure mechanism systems with ultra-high precision motion stages are increasingly being used for several applications including micro-measurement, micro/nano manipulation, microfabrication, data reading, writing on CD and so on. Flexure linkages offer inherent advantages of being frictionless, highly repeatable, and having great design flexibility. Their main advantage is that they can be manufactured monolithic which is extremely crucial for micro and nano-scale applications. But Monolithic fabrications of these mechanisms limit the use of multiple materials in the system and hence become expensive especially for three dimensional mechanisms. For large range flexure mechanisms monolithic fabrication is a costlier affair. Efforts have been made by researchers to come up with assembly procedure to assemble these mechanisms without over constraining them. Our paper discusses one such type of method to design and assemble various components of these mechanisms. The proposed guidelines which are based on criterion similar to Grubler's include a very simple formulation to determine number of locating pins to be used in assembly and also their locations of these pins. A z-stage flexure mechanism was fabricated and assembled using these guidelines and found it to be working perfectly with repeated assembly and dis-assembly.

Keywords: Flexure, bending, micro-fabrication, kinematics of linkages, constraints

1 Introduction

Flexure mechanisms offer considerable advantages over conventional motion systems [1], [2] in terms of operational characteristics. For example, flexure mechanisms have no friction loss and hence do not require lubrication. They generate smooth, continuous and repeatable displacement without backlash. These attributes have endeared flexure mechanisms to Meso- and micro-scale ultra-high precision, high-speed motion applications, including Microstereolithography [3], nanopositioning platforms [4], comb drives [5] in micro-electromechanical systems (MEMS), and so on. In case of flexure based motion platforms, the quality of motion is substantially better compared to air or magnetic bearings, the quality of constraint

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may be non-ideal yet it exhibits a predictable and repeatable relationship between force and displacement.

Flexure mechanisms are designed traditionally using monolithic construction and fabricated using either water jet machining [6], or wire Electro-Discharge-Machining (EDM) [7]. For nano and micro-scale applications monolithic construction is necessary but for large range mechanisms which are significantly big, it turns out to be a costlier process. There are natural advantages of using non-monolithic assembled flexure mechanisms. These include optimized use of materials, ease of fabrication, cost saving, etc. Only a few researchers [8] [9] have used assembly of flexure links and dealt with the overconstraining problems faced [10] [11] [12] for assembly. In this paper we introduce one such strategy to assemble the flexure mechanism. Traditionally, assembly of flexible links/joints using conventional principles of location [13] [14] [15] is carried out using two dowel pins at each end to secure completely each flexural link. Another way is to hold all the links in the mechanism in place by using specially designed fixtures and then tighten screws in all joints without using dowel pins for locating. We used both of these ways for assembly of a simple double flexure parallelogram mechanism. It was found that in the first case the linkages show warping even if the close machining tolerances are maintained. The second way though can give mechanism free of warping, is expensive and tedious especially for 3D flexure mechanisms.

In this paper we discuss a technique which is a hybrid of the above two. We propose guidelines for assembly of such mechanisms which holds for different topologies. A z-stage mechanism was built using proposed guidelines to corroborate the validity of the technique experimentally.

This paper is organized as follows: Section II uses the mechanism theory to develop a rule for formulating assembly guidelines. Several cases of assembly configurations are considered for the same and are further generalized. Section III presents application of these guidelines to design a z-stage flexure mechanism along with experimental results to a few cases. It brings out physical insights into the proposed rule.

2 Assembly Guidelines

The most commonly used flexure mechanism is double parallelogram flexure/folded-beam flexure/crab-leg flexure unit as shown in Figure 1. A simpler half part (parallelogram) of this mechanism is shown in Figure 2 as the isometric view of the practically realized equivalent system. The main base link is the fixed link and the stage is connected to the fixed link via the flexure links. For assembling this system, we will use dowel pins to locate the flexure links with respect to the ground link and stage. Locking plates are used to secure them together with screws. The screws do not take any part in locating as the corresponding holes in the flexural links are larger so they do not come in contact with the screws.

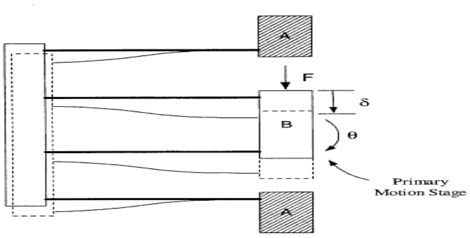

Figure 1: Double Parallelogram Flexure Mechanism [16]

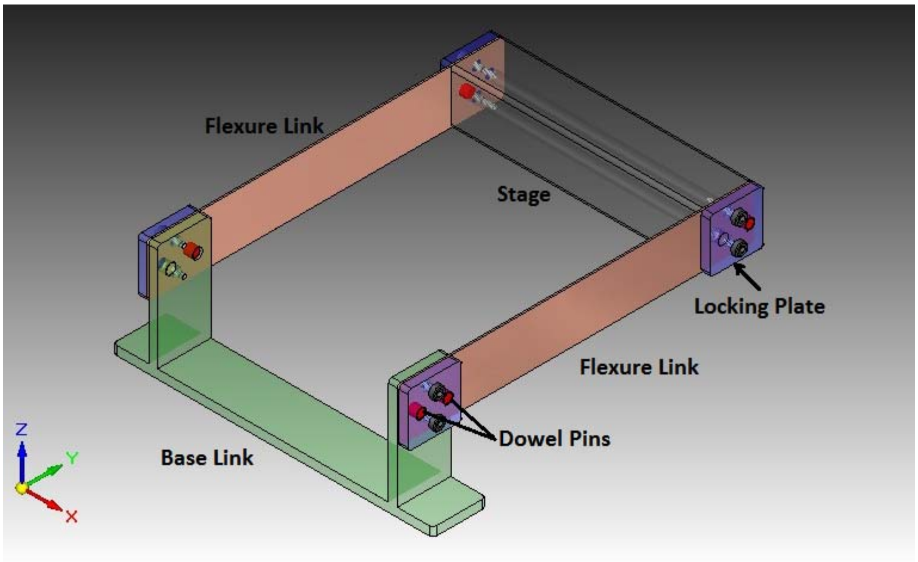

Figure 2: A 3-Dimensional Four Bar Linkage

Our goal is - Given such a flexure mechanism system, to determine the number of dowel pins to be used for locating links during assembly and their preferred locations so as to achieve warping free assembly in the presence of errors introduced due to dimensional tolerances.

To develop the assembly guidelines, the first proposed step is to consider a virtual system where flexure linkages are replaced by rigid links. We now present the following rule to fully constrain the flexure mechanism with over constraining it.

Rule: Use Grubler's criterion* [17]*, to find the number of joints (which will correspond to number of dowel pins to be used, both full and half joints) to fully constrain the assembly i.e. to have exactly zero degrees of freedom.

The Grubler's criteria for finding dof for a 2D mechanism is given by the following equation,

$$\mathbf{Dof = 3(n-1) - 2j - h} \qquad (1)$$

where “n” are no. of links, “j” are no. of revolute joints (pins in cylindrical holes) and “h” are the no. of higher pairs or half joints (pins in oblong holes). From the above formula the of number of full joints are given by

$$\mathbf{j = 3(n-1)/2 - h/2} \tag{2}$$

where, “h” is selected appropriately to make “j” a whole no. Now the table below shows the number of links and the number of joints required as per the equation given above to constrain the mechanism exactly, i.e. to form a structure with exactly zero degrees of freedom.

Table 1: Table Showing No of Half Joints

No of links (n)	No of Full Joints (j)	No of Half Joints (h)
1	0	0
2	1	1
3	3	0
4	4	1
5	6	0
6	7	1

From the formula above we observe that without employing the half joints for even number of links, the mechanism with zero DOF should have a fraction for number of joints which is not possible. Hence, we apply half joints wherever necessary.

Below Figure 3and Figure 4 is an example that shows how as per the table above a two link mechanism can be constrained by one full joint and a half joint.

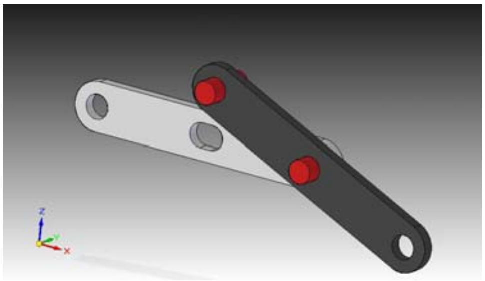

Figure 3: Two Link Mechanism

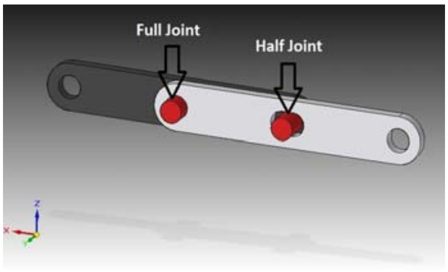

Figure 4: Constraining of dof

Here we have two links with a single joint in between them. As per Grubler’s criteria without employing half joint the number of joints required for constraining two links is 1.5. So in order to get a whole number for number of full joints we require a half joint to constrain the two links as shown in the figures above.

Consider a case with four bar mechanism. As per the rules we require 4 full joints and 1 half joint to fully constrain it. There are many ways this half joint can be introduced into the assembly. Some of them given below:

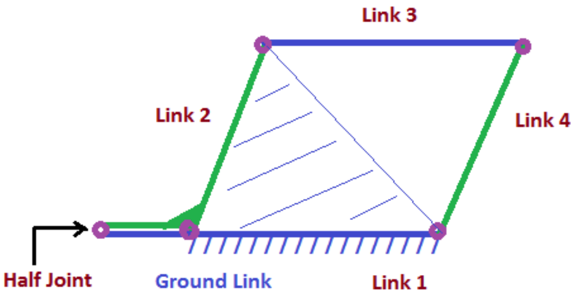

Figure 5: Half joint is between Ground Link and Link 2

Other possible ways are seen as in figure 6, figure 7 and figure 8:

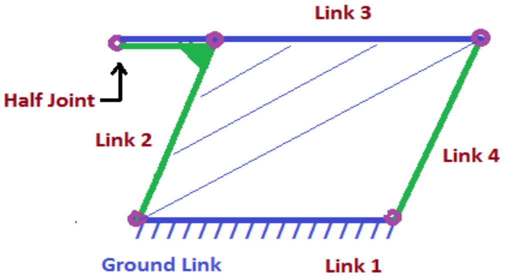

Figure 6: Half joint is between Link 2 and Link 3

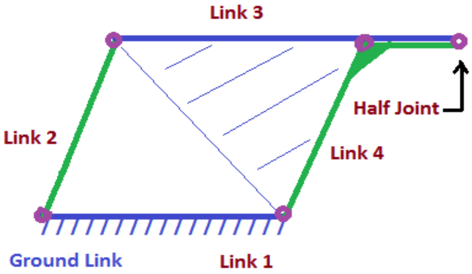

Figure 7: Half joint is between Link 3 and Link 4

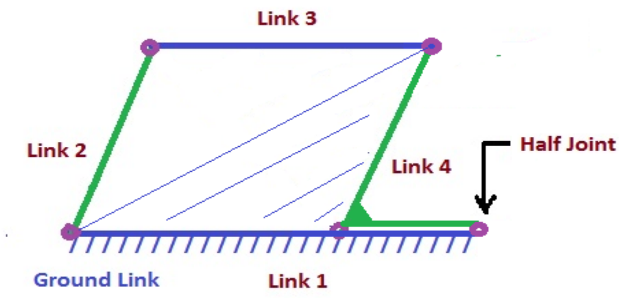

Figure 8: Half joint is between Ground Link and Link 4

Figure 9 is a particularly special case where there is no joint between link 3 and 4. By replacing a full joint by two half joints we can get similar results. Here we have 3 full joints and 3 half joints.
dof = 3(4-1) - 2(3) - 3 = 0
The links 3 and 4 in this case are secured together just by sand-witching due to the locking plate.

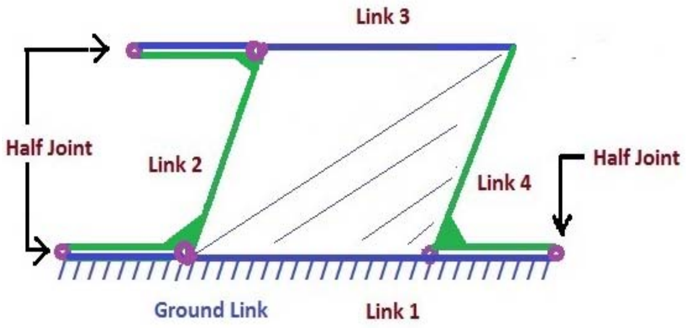

Figure **9:** Three half joints between Ground Link and Link 2, Link2 and Link 3 and Ground Link and Link 4

3 Application of guidelines and Experimental Results

This section presents systematic application of rules 1-3 to the z-stage flexure mechanism. The prototype designed using this technique demonstrated successful operation even after repeated assembly and disassembly.

Z-stage Flexure Mechanism:
This consisted of 4 flexure and 3 rigid links in configuration shown in Figure 10. Here the required z-stage flexure mechanism can be synthesized in two four bar parallelograms with one link common between them i.e. is a total of 7 links. For each four bar as per Rules 1, 2 and the accompanying table we require 4 full joints and 1 half joint to fully constrain it. Thus we would require 8 full joints and 2 half joints

for this 7 link mechanism. Figure 10, 11 and 12 shows different CAD views of the z-stage mechanism.

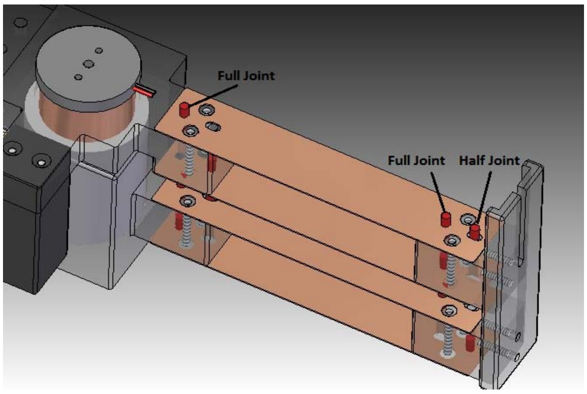

Figure 10: Perspective View with the Joints shown

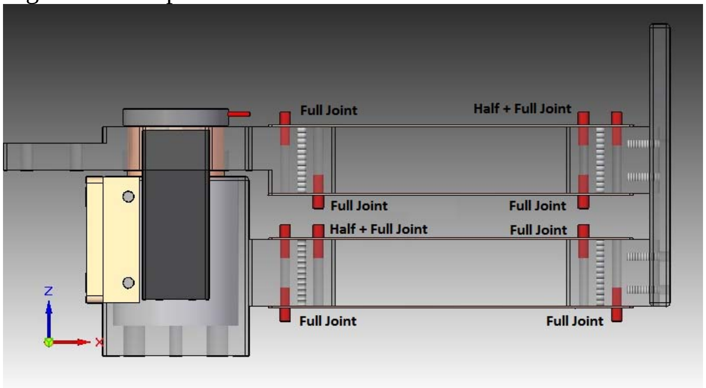

Figure 11: Pin (Joint) configuration for z-stage mechanism

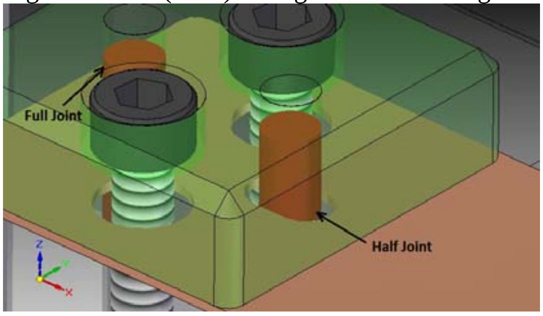

Figure 12: Detailed View of how half joint is employed (oblong slot in flexure link for half joint)

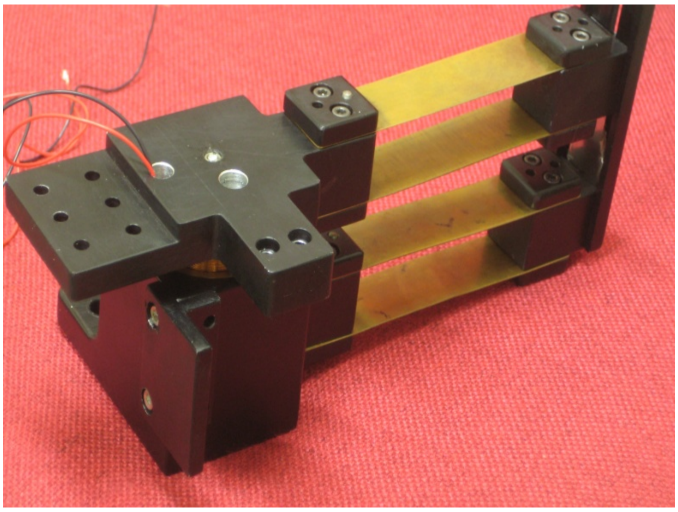

Figure 13: Fabricated z-stage flexure mechanism

Figure 13: Fabricated z-stage flexure mechanismshows the actually fabricated z-stage mechanism assembled using the proposed guidelines and tested to be working successfully. Note that a locking plate is employed at both ends of all flexural links to hold them in place along with the locating pins. Two screws (which do not participate in locating part because the corresponding holes in flexure links are much bigger) secure the locking plate in place.

4 Conclusion

This paper considered assembling flexure mechanisms as against fabricating them in monolithic fashion. One of the main challenges in doing so is to first avoid warping of links which deteriorates performance and further make assembly and disassembly easy and repeatable. The problem is looked at from the rigid body mechanism perspective and it is proposed to have DOFs to be exactly zero while determining the number of dowel pins (which are considered as rotary joints). Two additional rules are arrived at introducing a new concept called “half joint”. The concept helps in achieving the final assembly. Physical insights into the proposed rules are developed by case study that considered assembly using and not using the proposed rules. Finally two actual mechanisms are demonstrated to be successfully assembled and tested for their working. The proposed guidelines can be useful in developing more complex flexure mechanisms in non-monolithic fashion.

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