On the Novel Compliant Remote Center Mechanism

Prasanna S Gandhi
Department of Mechanical Engineering,
Indian Institute of Technology Bombay,
Mumbai, India
gandhi@me.iitb.ac.in

Rupesh S Bobade
IITB-Monash Research Academy,
Indian Institute of Technology Bombay,
Mumbai, India
rupeshbobade@iitb.ac.in

Chao Chen
Department of Mechanical and
Aerospace Engineering,
Monash University,
Clayton, Melbourne, Australia
Chao.chen@monash.edu

***Abstract*- Remote center motion (RCM) mechanisms provide manipulation over a circular arc about a distant center point. Different techniques to achieve such RCM can be classified as those providing either a virtual RCM or a real mechanical RCM. The mechanical RCM mechanisms are being used for minimally invasive surgery that imposes constraints on the end effector or surgical tool motion. In this paper, we propose a novel design (Patent file no.: 187/MUM/2013) which uses compliant links to generate the desired real RCM. Challenge involves generation of real RCM in such a way that the cross axis stiffness is very high as compared to the desired rotation stiffness with high accuracy in maintaining the RCM. The proposed compliant remote center motion mechanism (CRCMM) is conceived with angular arrangement of two compliant links connected to a motion stage. Under the applied force, this arrangement makes the links undergo simultaneous bending and twisting which results in the desired RCM. Extensive non-linear FE analysis is carried out to demonstrate accuracy of the RCM for the case under consideration. Further the mechanism is fabricated and preliminary experiments are carried out.**

Keywords—remote center motion; real remote center motion; compliant mechanism

I. INTRODUCTION

The movement over a circular arc having fixed radius about an iso-centric point is defined as remote center motion (RCM). RCM synthesis permits rotation around a distance fixed point without any physical revolute joint at that location [1]. Among different techniques available, the most used approaches are virtual and real RCM. In virtual case RCM is achieved through computer control where mechanism generates RCM virtually without having an actual physical constraint using kinematics or dynamics of mechanism [2-9]. Even with ease of achieving RCM virtually, this method is mostly considered as less safe due to violation of dexterous workspace under noisy situation. In real case, RCM is achieved through a suitable kinematic synthesis [10-15]. The mechanically generated RCM benefits with increased safety compared to virtual RCM and simplified inversed kinematics. Parallelogram mechanism and spherical linkage mechanisms are mostly used real RCM mechanisms. These RCM based constraint mechanisms have several applications like in space, undersea, mining, construction, and medical [16]. The famous da Vinci robotic system [17] used for laparoscopic surgery is a novel designed robot which achieves real RCM using parallelogram mechanism. Overall real RCM generated using rigid links mechanism have weaknesses of mechanical errors and frictional losses while the virtual RCM generated through computer control shows limitation over the accuracy of tool manipulation under noisy situation in addition. In this paper we introduce a novel way of achieving real RCM using compliant mechanism (Patent file no.: 187/MUM/2013). It can also be termed as complaint remote center motion mechanism (CRCMM). The proposed CRCMM is conceived with leaf flexure links which achieve the desired RCM under the application of force which induces simultaneous bending and twisting in them because of peculiar boundary conditions imposed in design. The design involves the challenge of achieving real RCM while keeping high stiffness in undesired directions of motion. The use of compliant links over rigid links for achieving real RCM makes the proposed designed mechanism ‘unique’. Compliant nature of these mechanism give them several benefits including no friction, no wear and tear, enhanced precision, easy control and low power. These benefits are especially useful towards high precision surgeries such as neural, vitreoretinal surgery. The FE analysis results generated in ANSYS confirms the accuracy of desired remote center motion. The following sections of paper contain the step-by-step synthesis of proposed CRCMM.

This paper is organized as follows: Section II presents step-by-step development of the proposed mechanism with one DOF motion with remote center. Section III then presents FE analysis with ANSYS to demonstrate that the RCM accuracy and parasitic errors obtained with such mechanism are negligible even for very high precision mechanism. Section IV presents the actually fabricated mechanism and details of assembly and experimental results confirming the working. Finally, Section V concludes the findings.

II. A NOVEL COMPLIANT RCM MECHANISM

This section develops the basic concept of the proposed compliant RCM mechanism in a step-by-step manner and compares it with a double parallelogram flexure mechanism as a special case.

Consider a mechanism obtained with just two compliant links arranged at an angle with respect to each other as shown in Fig 1. One end of both these links is fixed and at the other end a rigid member P is connected. When the force is applied on P the deformation occurs in such a way that the links undergo bending and torsion at the same time with both the boundaries having slope zero in the direction of bending. Although theoretical analysis for such deformation is out of intended scope of the paper, the simulations carried out in the next section indeed indicate that the rigid link P moves along a circular arc. The center of this circular arc happens to be the intersection O shown in Fig 1.

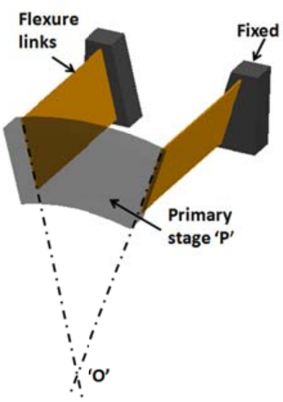


Fig 1: Isometric view of 2-links compliant mechanism with RCM

One can see this intuitively considering an extended version of this mechanism when the links are arranged on a full circle as shown in Fig 2. When force is applied, the stage P1 would rotate about a longitudinal axis passing through the center of this circle. In this case as well the links undergo combined bending and twisting. Twist in each of the links is equal to the angle of rotation. Parasitic rotation of the stage P1 about an axis other than the longitudinal (see Fig 2) is prevented because of high flexural rigidity in other directions owing to much larger width of compliant links as compared to thickness. Based on this mechanism one can project that the proposed mechanism in Fig 1, which is a part of sector of full circle considered in Fig 2, would also demonstrate a similar effect i.e. motion about longitudinal axis passing through point O.

Although the mechanism proposed in Fig 1 would work for getting a RCM, it would also introduce parasitic error of axial deflection in longitudinal direction. This parasitic motion is attributed to the fact that the beam length is constant (the stretching of the neutral axis of the beam is negligible). Hence bending of beam, especially considering large deformations, would lead to longitudinal motion of stage P which is not desired. To compensate for this parasitic motion an additional motion stage (secondary motion stage) is now introduced as shown in Fig 3. With equal force on both the primary and the secondary stage, their motions would be identical when all four links are identical. However, parasitic motion of the primary stage would be compensated by parasitic motion of the secondary stage. Hence for the RCM of the primary stage there would be no parasitic motion.

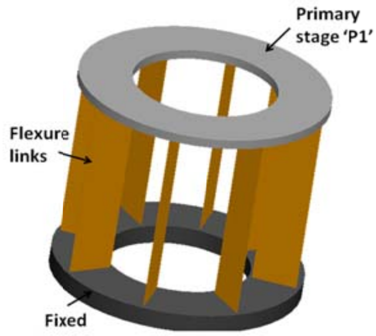


Fig 2: Compliant mechanism with links arranged on full circle

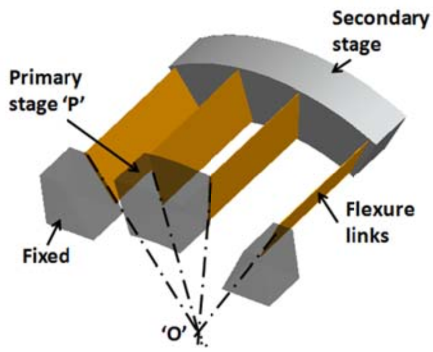


Fig 3: Isometric view of 4-links compliant mechanism with RCM

A double parallelogram mechanism used widely in the literature (see for example [18]) is a special case of the proposed mechanism when the angle between the links attached to both the stages is zero. Thus the compliant links become parallel to each other and mechanism reduces to a double parallelogram compliant mechanism. For such mechanism the remote center of motion would be at infinity.

III. FE ANALYSIS AND RESULTS

This section presents nonlinear finite element (FE) analysis of the proposed mechanism. Because of the large deformations involved (deformations are several times the thickness of compliant linkages), a nonlinear FE analysis is required considering geometric nonlinearities. Specifically the axial deformation of beams is going to be limited as compared to bending or twisting and hence length constraints on the beam would introduce geometric nonlinearities.

The details of nonlinear FE analysis using ANSYS are as follows: The element used for rigid components and compliant links is solid tetrahedron 187. Since the thickness of compliant links is very small the smart element size of 20.5µm is used. Convergence analysis was carried out by increasing the number of elements till the results of deformation did not show appreciable change. (see Figs 4 and 5 for convergence analysis test for two links and four links compliant RCM mechanism respectively).

The following cases are considered for FE analysis:

1. Case 1: Mechanism shown in Fig 1 (See Fig 6)
2. Case 2: Mechanism shown in Fig 3 (See Fig 7)

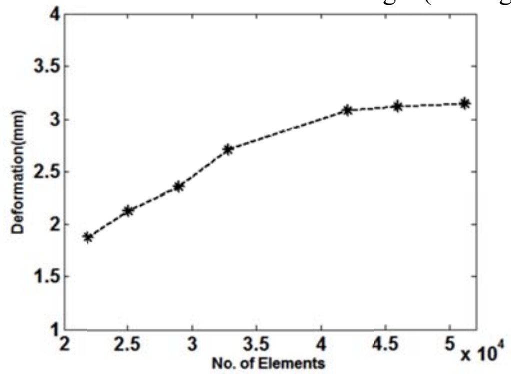


Fig 4: Convergence test for two links RCM mechanism

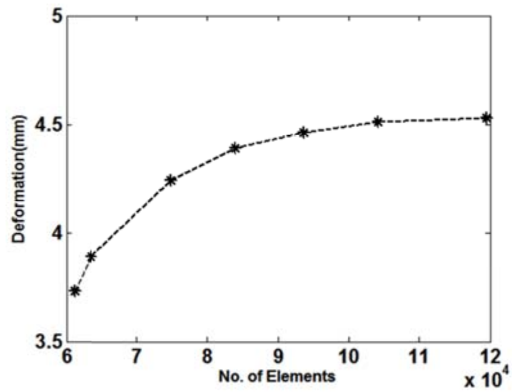


Fig 5: Convergence test for four links RCM mechanism

We run several simulations to finally check the accuracy at RCM point and to get the parasitic errors in longitudinal and other directions in both the cases as the angle increases. As we compared the parasitic error motion in 'z' direction for two links and four links case, it is found as shown in Fig 8 that in Case 1 the parasitic error increases as the force and hence the deflection goes on increasing; however in Case 2 parasitic error in longitudinal direction is almost zero and stays constant even if the force is increased.

For two links, under considered material properties and boundary conditions (see Appendix A) shows maximum error of 2.4E-8 mm for 250mN load. Considering results of the analysis presented above, for the four links mechanism where the cross axis stiffness of flexure link is 0.198 N/mm against desired axis stiffness of 0.171N/mm for initial undeflected position, (See Appendix A for flexure link details), the RCM accuracy is established for longitudinal z direction. Figs 9 and 10, shows the displacement at RCM point in 'x' and 'y' directions under different loading considerations. It shows for a range of ±6 degrees movement is primary stage, the maximum displacement at RCM is ~2.21E-7mm in 'x' direction and that of ~8.5E-10mm in 'y' directions. These values are extremely small even if compared with micron tissue sizes present at surgical sites of high precision surgeries such as neural and vitroretinal surgery [19]. The deflection at RCM point is demonstrated here in Fig 11 with closer view. It clearly shows the intersection of initial position and deflected position of a virtual thin needle connected to the motion stage with its tip coinciding with the RCM point. (Note that the needle does not carry any force.

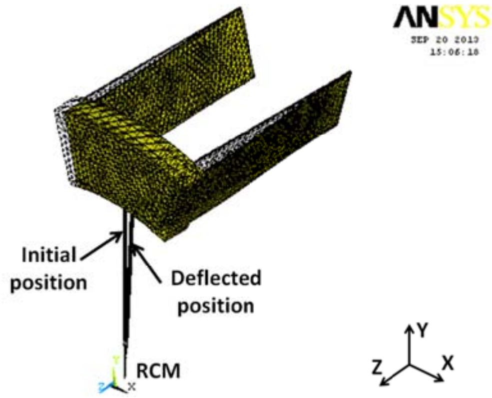


Fig 6: FE analysis of two links RCM mechanism

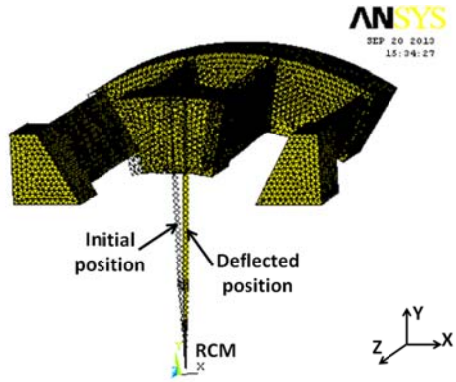


Fig 7: FE analysis of four links RCM mechanism

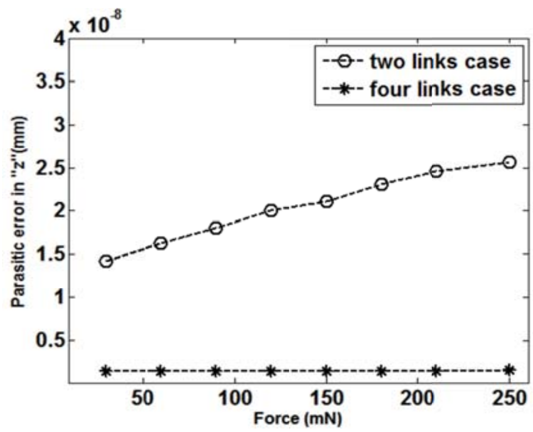


Fig 8: Parasitic error with 2-links Vs 4-links

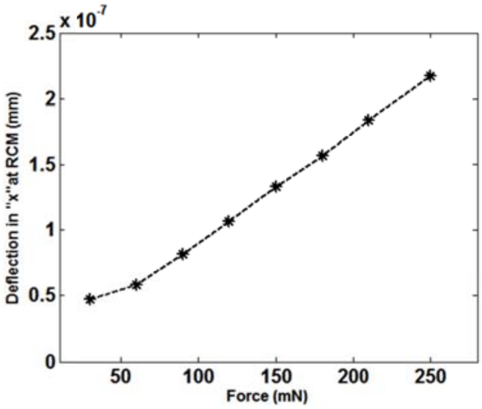


Fig 9: Deflections in ‘x’ direction at RCM

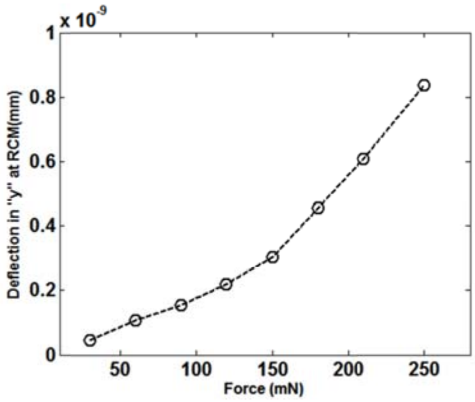


Fig 10: Deflections in ‘y’ direction at RCM

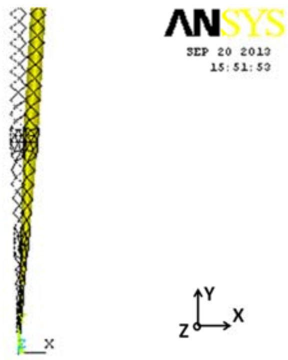


Fig 11: Closer view at RCM point

IV. Fabricted Mechanism and Experimental Results

This section presents the actually fabricated mechanism and details of assembly and experimental results confirming the working. Normally the compliant mechanisms are generated monolithic but considering the complexity in geometry the proposed mechanism is developed non-monolithic using AL HE30 for rigid components and spring steel for compliant links. The fabricated model is shown in Fig 12. To achieve accuracy and to avoid warping effect, the assembly process for non-monolithic case is carried out using the guidelines presented in reference [20]. The experiments are carried out by mounting a needle on primary stage as shown in Fig 13. In experiment deflections at the tip of needle is checked on graph paper with respect to RCM point of the mechanism.

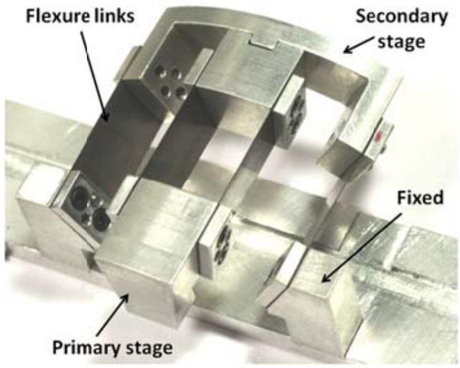


Fig 12: Fabricated mechanism

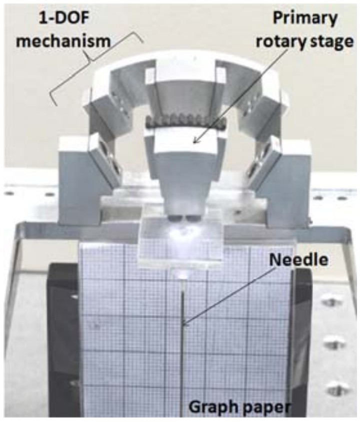
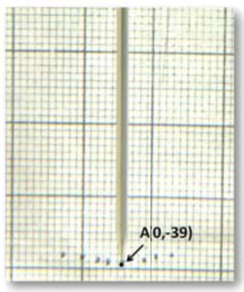
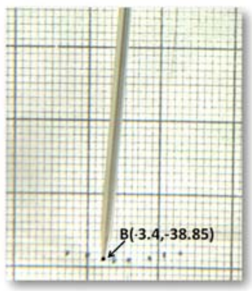


Fig 13: Experimental set-up

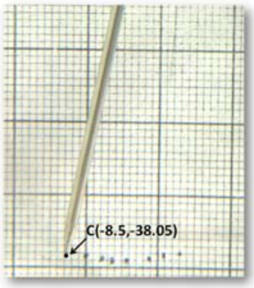
As shown in Figs 14(a-e), the tip of needle on graph paper shows the initial (or non deflected) position ‘A’ which is about RCM point at distance 39mm down in ‘y’ direction. For left movement of primary stage, the tip follows points ‘B’ and ‘C’ and for right movement it follows points ‘D’ and ‘E’. The respective coordinate positions of points ‘A’ to ‘E’ shows the movement of needle tip perfectly about an arc of circle having radius ‘~39mm’. In this way, the experimental results support the analysis results carried out in ANSYS although more accurate experiments are needed to get establish actually obtained levels of accuracy of the RCM point.



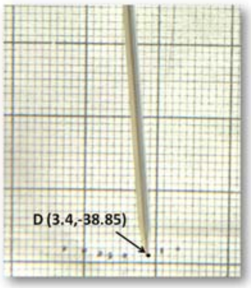
(a)



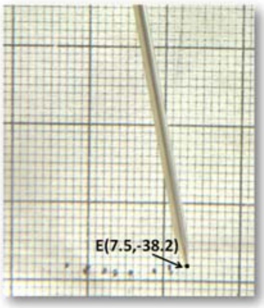
(b)



(c)



(d)



(e)

Fig 14: Experimental results

Considering the accuracy at RCM point, the proposed mechanism can be successfully implemented for high precision minimally invasive surgical cases where surgical tool can be mounted on primary stage to achieve required constraint manipulation about incision point. During surgery, surgeon has to match the RCM point generated through mechanism with incision for pivoted motion.

V. CONCLUSION

The novel design of compliant mechanism for remote center motion is proposed in this paper. A step-by-step design and development is presented. The proposed compliant remote center motion mechanism (CRCMM) consists of the leaf flexure links arranged at an angle with respect to each other. Upon application of force they undergo simultaneous bending and twisting to produce the desired remote center motion of the stage. The exhaustive FE analysis using ANSYS is carried out to demonstrate the accuracy of the proposed RCM considering errors in motion with respect to fixed desired RCM. Further the proposed mechanism is fabricated using recently developed assembly techniques and preliminary experiments support the proposed findings. The proposed designed indicates a potential application in high precision minimally invasive surgeries like neural and vitreoretinal surgery.

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Appendix A:

(I) The material properties, dimensions of flexure link used for analysis and experiments are as follows,

Material:
Spring Steel: E= 2.1E5 MPa, Density=7.85gm/cm^3, Poisso's ration=0.29

Dimensions: L=35mm, b=12mm, t=0.15mm, and
Angle between links of primary stage, θ=18^o

(II) Boundary conditions for flexure link used,

At fixed end: y=0 and dy/dx=0
At free end: dy/dx=0

Where,
E: Young's modulus of material
L: Length of flexure link in 'mm'
b: Width of flexure link in 'mm'
t: Thickness of flexue link 'mm'
y: Deflection in 'mm'