**PROGRESS REPORT (Year 2018-19)**

File No: (ECR/2016/000760)

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| **1. Project Title:** *Design and Development of Three Axis Flexural Stages for Micro-milling Workstation* | **DST No:** *ECR/2016/000760* |
| **2. PI (Name and Address):** *Dr. Kiran Suresh Bhole, Associate Professor, Department of Mechanical Engg., Sardar Patel College of Engineering, Andheri (West), Mumbai 400058* | **Date of Birth:** *10.03.1977* |
| **3. Co-PI (Name and Address):** *Nil* | **Date of Birth**: *NA* |
| ***4.*** **Broad areas of Research:** *Engineering Sciences* | |
| 4.1 Sub Area: Mechanical Engineering; Design and Manufacturing | |
| **5. Approved Objectives of the Proposal:** Objective 1: Design and development of double flexural XY stage<br>Objective 2: Design and development of spiral shaped flexural Z-stage<br>Objective 3: System integration for the development of micro-milling workstation<br>Objective 4: Characterization of dynamics of the flexural stage based micro-milling workstation<br>Objective 5: Fabrication of complex shaped microstructures using developed micro-milling workstation. | |
| **Date of Start:** 25th November 2016 | **Total cost of Project:** Rs. 19,92,120/- |
| **Date of completion**: 24th November 2019 | **Expenditure as on:** 25th November 2019<br>Capital (Non Recurring) – Rs. 1432827/-<br>General (Recurring) – Rs. 124674/- |

**6. Methodology :**

***a. Methodology to realize Objective 1:*** *Design and development of double flexural XY stage*

XY stage is consists of double flexural mechanism (DFM) as shown in Figure 1(a). It consists of two fixed blocks marked as A, four flexible beams, primary motion stage B, and secondary motion stage. For the working of mechanism actuating force F is applied on primary motion stage. Design of XY flexural mechanism mainly involves determination of the length, width and thickness of the flexible beams (Beryllium copper strips are used because of its high fatigue strength) used in double flexural mechanism. Dimensions of flexible links are designed considering static forces (due to stiffness of beams) and dynamic forces acting on the primary motion stage in the project. Non-contact sensors (optical/magnetic encoders, refer Figure 6 (c)) and actuators for each of the flexure stages are chosen so that desired positioning accuracy is achieved. Actuators with linear optical encoders (Renishaw Encoders) are co-located on XY flexural mechanism to have an ease of control despite of non-linear flexibility effects. However, practically it is observed that due to lateral chattering the stage is unstable. Hence, lead screw based ball bearing supported stages are used for XY motion required for milling stage.

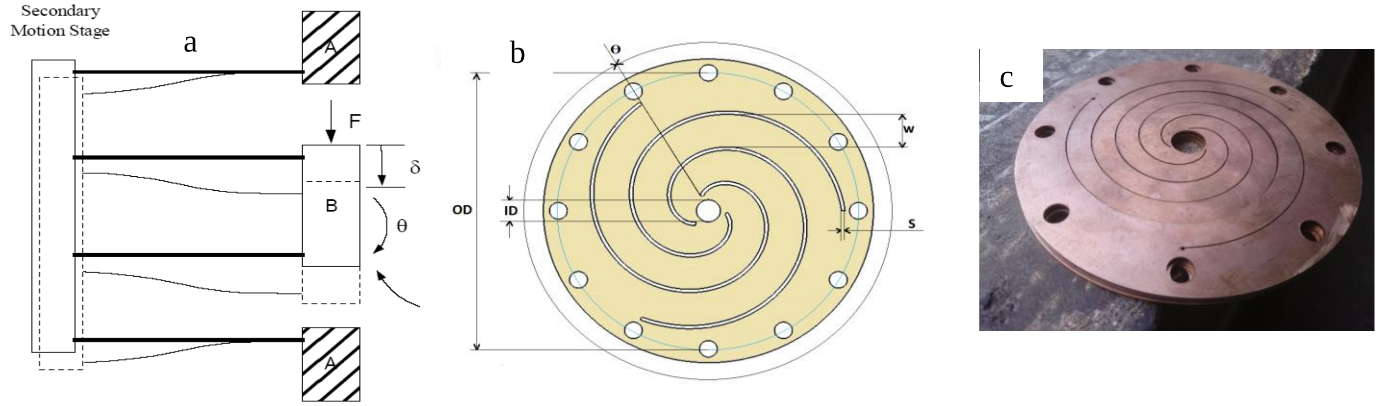


Figure 1: (a) Double parallelogram flexural system for XY stage (b) CAD model of 3 arm flexural disc; (c) fabricated spiral shaped flexural disc to form flexural feed stage.

***b. Methodology to realize Objective 2:*** *Design and development of spiral shaped flexural Z-stage*

Figure 1(b) and (c) shows the CAD model and actual photograph respectively of one of the discs of the spiral arm flexural Z-stage consists of three spiral slots. In flexural Z-stage, assembly consists of two sets of parallel stacked flexure discs interspersed with central and peripheral spacing rings (see Figure 2 (a)). High radial stiffness and low axial stiffness is the desirable criteria for the flexural system for an application of Z-stage of micro-milling workstation. This is because for the feed in machining, the axial motion against actuation force is desired along with arresting radial displacement due to error in assembly or actuation. Spiral stacked flexural assembly bears the undesirable radial and desirable axial loads generated while machining process. Considering the criteria, the parametric study of the flexural arm is studied and based on the analysis, each spiral traverses of an angle of 540° is selected for the application. The final converge flexural stage after analysis consists of a two stacks (each of 2 flexural discs) formed so as to have high radial stiffness and low axial stiffness with enough strength (refer Figure 2 (b)). The collet and tool holding assembly is selected for holding the cutting tool. BLDC motor is selected to impart cutting torque to the cutting tool.

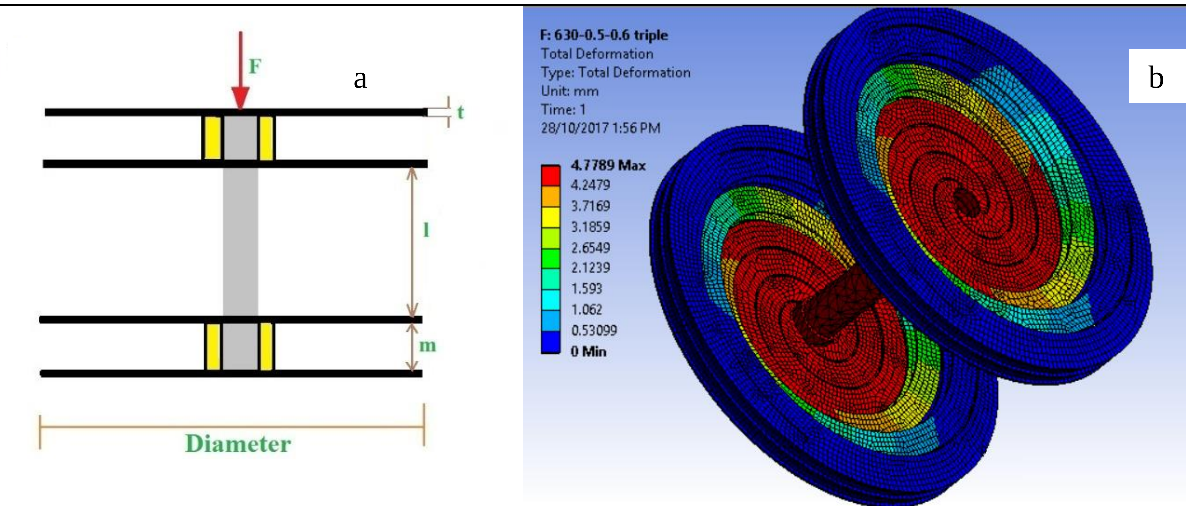


Figure 2: (a) Assembly of 3 arm flexural disc for z-stage; (b) FE Analysis of flexural z-stage.

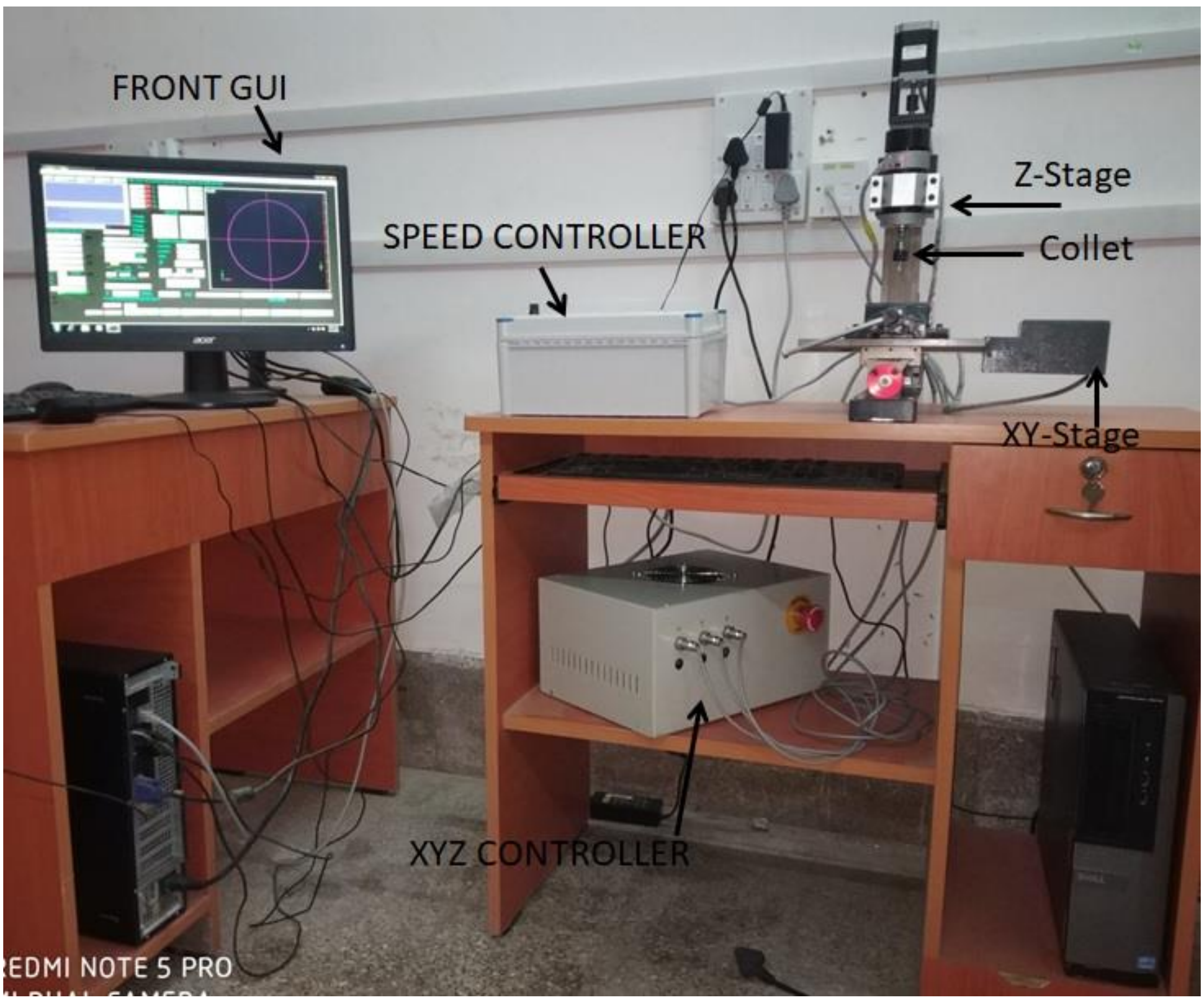


Figure 3: Actual system of micro-milling workstation.

c. ***Methodology to realize Objective 3:*** *System integration for the development of micro-milling workstation*

After design and fabrication of the XY flexural stage and spiral arm based flexural Z-stage, the appropriate actuators and sensors are embedded for actuation of stages and purpose of position sensing for feedback respectively. Figure 4 shows the schematic representation of system integration for micro-milling workstation. The voice coil actuators and flexural systems are best suited for the proposed application for XY stages. The data acquisition system, dSPACE DS 1104 (refer Figure 6 (c)) is purchased for interfacing of subsystems of the micro-milling workstation. The actual data from the system is acquired from the encoders employed in the system.

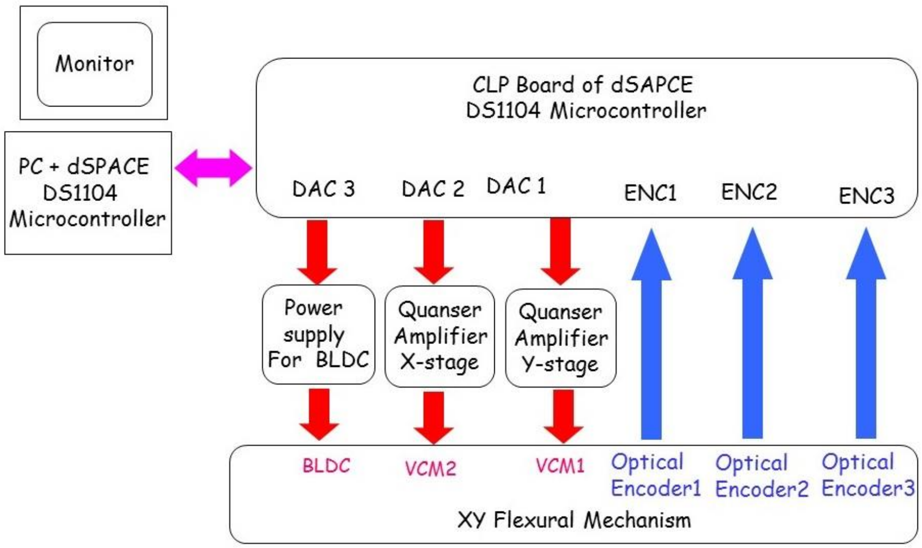


Figure 4: System integration for micro-milling workstation.

***d. Methodology to realize Objective 4:*** *Characterization of dynamics of the flexural stage based micro-milling workstation*

The effect of different parameters of the flexural discs such as diameters, thickness, spiral angle and spacing distance are observed in finite element software (ANSYS) for displacement, radial and axial stiffness (refer Figure 2(b)). Furthermore these resuts are validated through experimental study. The simulation and experimental results are presented in the non-dimensional form for its generalization (refer Figure 6 (a)). In analysis (z/d), (s/d), (p/d) and (t/d) are dimensionless axial displacement, spacing, spiral pitch and flexural plate thickness respectively (refer Figure 1(b), 2(a) and 6 (a)). The conclusion of results in non-dimensional form has provided generalized design guidelines for the similar kind of systems (refer Figure 6(a)). Based on this analysis, the details of systems are finalized and manufactured. The assembled developed system is characterized under different operating parameters experimentally before actual fabrication of the microstructures. The dynamic characteristics of the flexural stages under displacement are observed. The different scan velocity is provided to the XY stages through actuators. The real time system data is captured by the data acquisition system dSPACE DS 1104 for the accuracy in linear guidance and is analyzed for axial displacement against maximum stress, radial stiffness and axial stiffness using force and strain gauge sensors.

***e. Methodology to realize Objective 5:*** *Fabrication of complex shaped microstructures using developed micro-*

*milling workstation*

The developed z-stage of the system is used to drill holes of different sizes. The CAD model of holes and actual drill holes are shown in Figure 5. The smallest desired hole size is 50 microns with maximum being 500 microns. The intermediate holes are of 100, 150, 200, 300 and 400 microns. The error is calculated by comparing the diameter of obtained drill hole with corresponding CAD dimension. The error obtained through characterization is limited to 18%. The maximum error is seen for intended drill size of 50 microns. Now using XY stages the system will be used to fabricate the complex shaped microstructures. Various application oriented structures such as typical micro-channels will be fabricated through micro-milling workstation. For fabrication of these structures, first CAD model of the structure will be developed. For the intended structure, the scan path of the milling cutter will be decided and coded in G and M program. This scan path data will be deployed directly to the microcontroller. The data from the microcontroller will be then provided to the concern actuators of the XY stage through DAC channels and current amplifier. Before commencement of the scan path of the workpiece, the depth of the milling will be provided through high resolution z-stage and rotational torque to the milling cutter through BLDC.

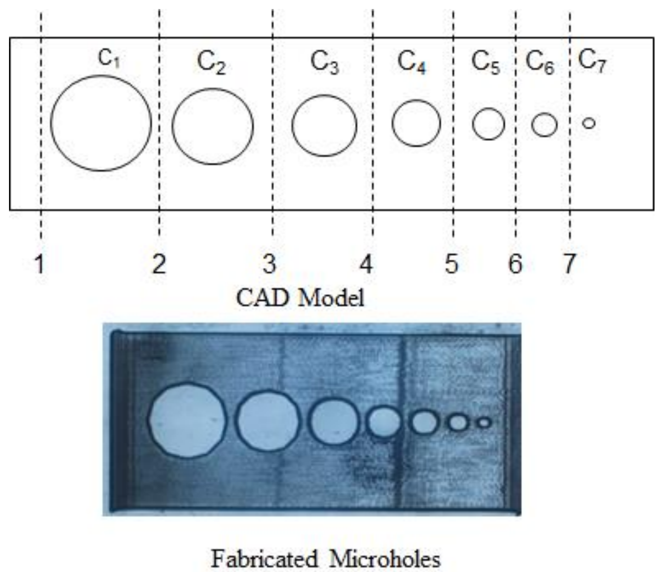


Figure 5: CAD drawing and optical microscope images of the micro-holes.

**7. Salient Research Achievements:**

**7.1 Summary of Progress**

a) Simulation work:

The 3 arm double stage spiral shaped flexural system is characterized with finite element method. The characterization is presented in non-dimensional way for its generalization. Based on this exhaustive characterization, the graphical design tool is developed (refer Figure 6(a)). Further based on this developed designed guideline the production drawings for the micro-milling workstation are prepared.

b) Experimental work: The stages of the micro-milling workstation are experimentally characterized. The accuracy of the stages is identified experimentally. These data is generalized using dimensionless parameters. Based on generalized characteristics the design procedure is laid. This generalized procedure can be used for any engineering application using spiral based flexural system.

c) Procurement of equipment:
Major equipments required for the project is purchased (refer Figure 3). The testing of these equipments is done and is commissioned. The customized components are then designed based on the purchased standard equipments and developed methodology. The system is now ready for manufacturing.

7.2 New Observations

Feed stage of the system consists of two stages three spiral arms is characterized considering different geometrical variables. The generalized design guideline for the similar kind of system is presented (refer Figure 6(a)).

7.3 Innovations

- Generalized design methodology for two stage three arm spiral shaped flexural system.

7.4 Application Potential

7.4.1 Long Term:

The long term potential applications of the work may be stated as follows:

- Development of machining centre for fabrication of microstructures in subtractive way.
- High resolution flexural system capable to develop accurate microstructures.

7.4.2 Generalized design guideline for multi arm multi stage spiral shaped flexural system.

7.4.3 Short Term:

- Training of under graduate and post graduate students in this domain.
- Research publications

7.5 Any other: ---

Research work which remains to be done under project :

- Objectives are attained satisfactorily.

Ph.D Produced No: 01 (in progress)

Technical Personnel Trained = 07

Research Publications arising out of the present project: 05

List of Publications emanated out of this Project (including title, author(s), journals & year(s):

(A) Papers published only in cited Journals (SCI): Nil

(B) Papers published in Conference Proceedings, Popular Journals etc. – 05

1. Kiran Bhole and Megha Janbandhu, "Design and Development of Double Spiral Shaped Flexural Feed Stage for Micro-drilling Workstation", International Conference on Advances in Materials and Manufacturing Applications IConAMMA 2017, 17$^{th}$ -19$^{th}$ August 2017 Elsevier Materials Today Proceedings, vol.5, issue 11, part 3, (2018) pp 25468-25476.
2. Kiran Bhole and Vinit Sonavane, "Parameter Based Method for Three Arm Spiral Shaped Flexural Bearing" International Conference on Materials Processing and Characterization, Hyderabad, Elsevier

Materials Today Proceedings, 5 (2018) pp 19380-19390.

3. Vinit Sonavane and Kiran Bhole, “Frequency Analysis of Two Stage Three Arm Spiral Shape Flexural Bearing” 2nd International Conference on Frontiers in Engineering, Applied Sciences and Technology, NIT Tiruchirappalli, 2018.
4. Kiran Bhole and Vinit Sonavane, Static and Frequency Analysis of Triple Stage Three Arm Spiral Shape Flexural Bearing using FEA, International Conference on Advances in Materials and Manufacturing Applications IConAMMA 2018, 16th -18th August 2018.
5. Kiran Bhole and Sachin Mastud, Generalized Design Methodology for Three Arm Spiral Cut Compliant Linear Stage, 6th International Conference on Production and Industrial Engineering, 8-10 June, 2019.

Patents filed/ to be filed: Nil

Major Equipment (Model and Make)

| Sr. No | Sanctioned List | Procured (Yes/No) Model and Make | Cost (Rs. In lakhs) | Working (Yes/No) | Utilization Rate (%) |
|---|---|---|---|---|---|
| 01 | Collect, adapter, Cutting tools and other tool holding accessories | Procurement: Yes<br>Model and Type: Quattro, Model Number 3601, 200020623, 000005745, 000005948 | 0.63529 | Yes | 100% |
| 02 | Data Acquisition System (DAQ) and microcontroller | Procurement: Yes<br>dSPACE 1104 platform | 7.198 | Yes | 100% |
| 03 | Encoders | Procurement: Yes<br>Make: Magnetic and optical encoders, Renishaw, Models:<br>1. RGH25F R/HEAD 3m cable 15w-D,<br>2. REF INTERPOLATOR X1000 (6MHz)<br>3. LM1311CPRGAA10D00<br>4. LM13 INC PROG 1M 15 PIN D<br>5. MS10AM500A0000 | 1.9008 | Yes | 100% |
| 04 | Manual stages and positioning devices | Procurement: Yes<br>Make: Holmarc<br>Model: LMS150x150x50<br>HSN 9033 | 2.44791 | Yes | 100% |
| 05 | DC power supply | Procurement: Yes<br>24Volts DC<br>Octagon | 0.28320 | Yes | 75% |

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| 06 | Brushless DC motor with controller | Procurement: Yes<br>LXLWU3, GPMM1840, LXKSY5, GPMG4675, LXLWY4 | 0.60047 | Yes | 100% |
| 07 | Force Sensors | Procurement: Yes<br>Payload capacity 10 Kg; Octagon | 0.36580 | Yes | 75% |
| 08 | Linear Current Amplifiers | Procurement: Yes<br>11AMPS; Octagon | 0.44840 | Yes | 50% |
| 09 | Voice coil Actuators | Procurement: Yes<br>15 KN holding force: Octagon | 0.44840 | Yes | 50% |
| Total | | | 14.32827 | -- | -- |

Image of Equipment:

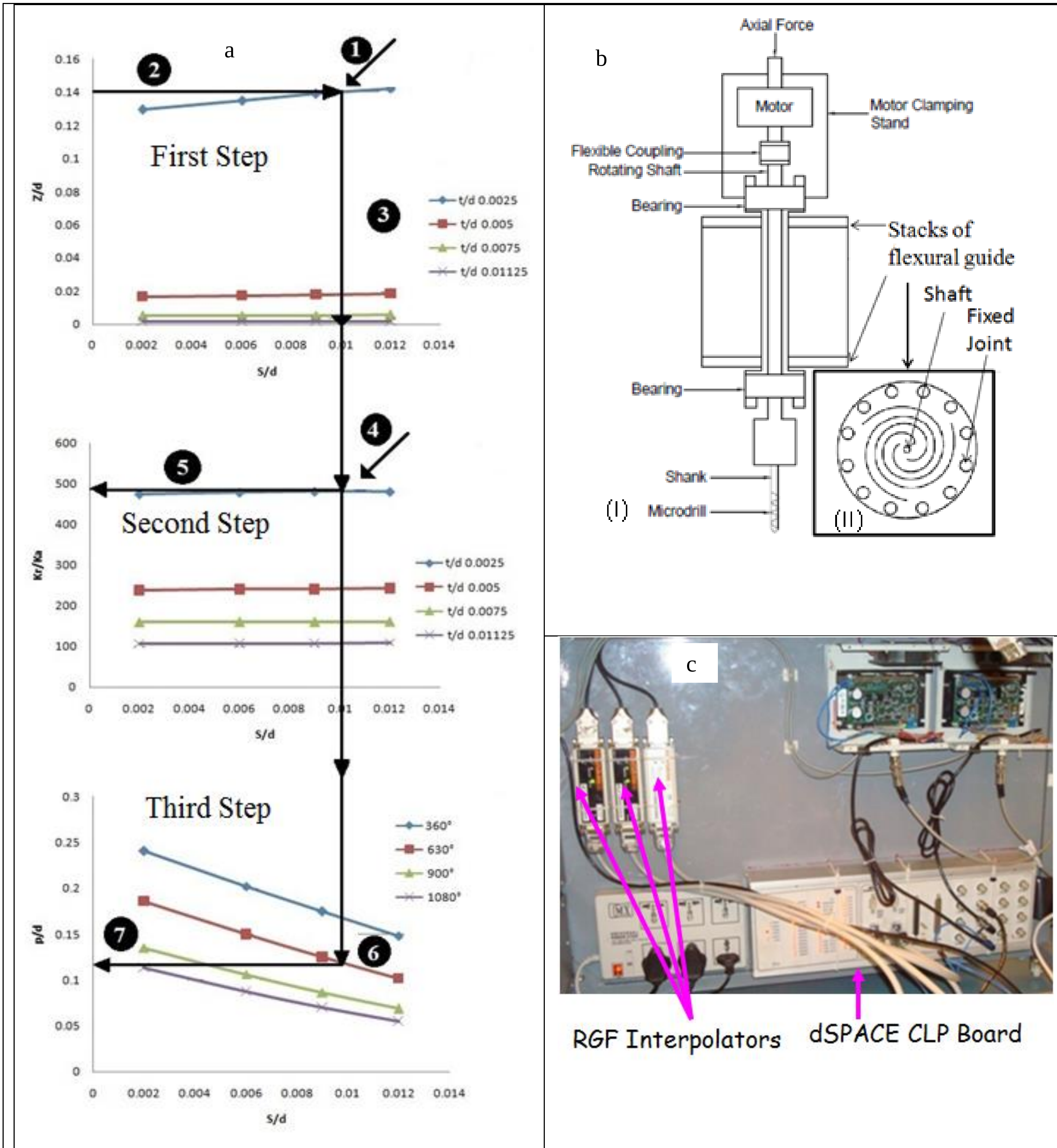


Figure 6. (a) Design method example for two layer three arm flexure system with Z/d=0.14 (b) Schematic of flexural z-stage of micro-milling (c) RGF interpolators of encoders and dSPACE 1104 DAQ platform.