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SYNTHESIZING PRECISION FLEXURES THAT DECOUPLE DISPLACEMENT-BASED ACTUATORS

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INTRODUCTION

The purpose of this work is to generate a deterministic approach for synthesizing flexures that decouple the actuators of multi-degree of freedom (DOF) precision motion stages. This approach utilizes the geometric shapes of the FACT synthesis approach [1] to help designers rapidly visualize and consider every flexure topology that may be used to decouple any set of displacement-based actuators (e.g., set-screw, piezo, thermal, and magnetostrictive actuators). The ability to correctly synthesize such flexures is important because they *(i)* improve the controllability of the system's stage by not allowing the output of one actuator to affect the output of the other actuators, *(ii)* minimize the stage's parasitic motion errors by only transmitting the intended motions through the flexures to the stage over the full stroke, and *(iii)* increase the life of each displacement-based actuator by reducing undesired loads (e.g., shearing, bending, or twisting loads) imposed by one actuator to the other actuators. This work most directly impacts the synthesis of large-stroke, low-speed, multi-DOF precision flexure systems that are driven by displacement-based actuators.

MOTIVATION

The problem of effectively synthesizing flexures that decouple displacement-based actuators has been a challenge for precision motion stage designers for decades. Although some designers have successfully generated concepts that optimally satisfy their design's specific functional requirements [2], no general systematic approach currently exists for helping designers consider every concept, which would optimally decouple the displacement-based actuators within any multi-DOF system.

FUNDAMENTAL PRINCIPLES

The principles of the FACT synthesis approach have been adapted to help designers consider every way any set of displacement-based actuators may be decoupled such that they may displace the system's stage large amounts without imposing damaging forces on other actuators. Before discussing how FACT may be applied to the synthesis of decoupled systems, consider first the three DOF system shown in Fig. 1A. The stage of this system is constrained by four bent blade flexures that permit the stage to move with two in-plane translations and one in-plane rotation. These DOFs are actuated by three piezo actuators shown as blue blocks in the figure. Every combination of these three DOFs may be achieved by simultaneously actuating these three actuators with various magnitudes. The actuators of the design from Fig. 1A are not decoupled. As one actuator expands, damaging transverse forces are imposed on the other actuators. These damaging forces become more problematic the farther the stage is displaced.

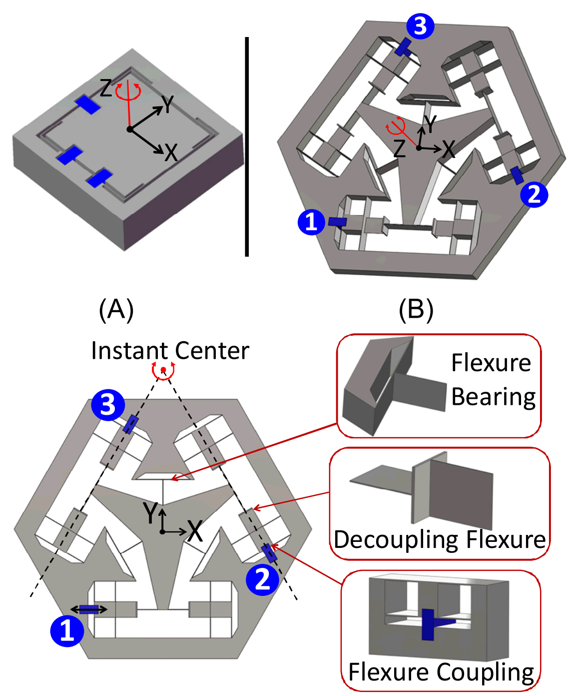


FIGURE 1. Three DOF flexure systems with coupled (A) and decoupled (B-C) actuators

Now consider the decoupled system shown in Fig. 1B-C, which was designed using FACT. This system would possess the same DOFs as the system in Fig. 1A, but its actuators would not experience the same undesired loads. If actuator 1 were actuated, the stage would rotate about the instant center shown in the figure independent of the two other rotations caused by actuators 2 and 3. Like most decoupled systems, the flexure topology of this system consists of three types of flexural elements as shown in Fig. 1C—flexure bearings, flexure couplings, and decoupling flexures. The job of flexure bearings is to guide the stage with its intended DOFs while constraining it to not move in other directions. The job of flexure couplings is to make sure that the stationary actuators are not subjected to any undesired loads except for those along their intended lines of actuation. The job of decoupling flexures is to prevent transmission of the motions induced by other actuators in the system to the flexure couplings of their corresponding actuator while permitting their corresponding actuator to stiffly transmit its intended motion to the system's stage.

Rules have also been created and integrated into the FACT synthesis approach for determining how much constraint each flexural element could contribute to the system for controlling exact, over, or underconstraint. Note that for the design of Fig. 1B-C, each serial actuation chain (i.e., the flexure chains consisting of the combined flexure couplings and decoupling flexures) is a six DOF flexure and thus provides no constraint to the stage. Thus, if the actuators were removed, the stage would be exactly constrained by the three flexure bearings to only possess the desired three DOFs. If each of the three actuators were locked in place such that their corresponding flexure couplings could not move, the stage would be totally exactly constrained and would not be able to move.

Not all decoupled flexure systems require separate flexure bearings to guide their stage with the desired DOFs like the design of Fig. 1B-C. FACT has also been adapted to enable designers to synthesize decoupled flexure systems that possess serial actuation chains, which not only decouple the system's actuators, but simultaneously act as bearings that guide the stage with the desired DOFs. Examples of such systems are shown in Figs. 2 and 3.

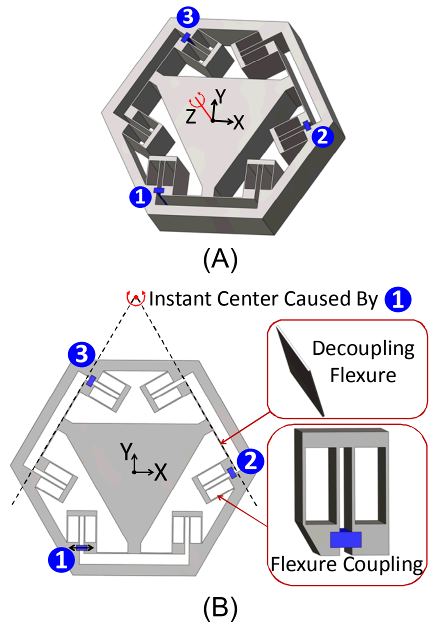


FIGURE 2. Another decoupled design (A) with its flexural elements labeled (B)

The biggest difference between these two designs is that the three actuators in the design from Fig. 2 are each uniquely linked to three instant center rotations, which may be combined to achieve the three desired DOFs (i.e., the two translations along the x- and y-axes and the rotation about the z-axis), whereas the three actuators in the design from Fig. 3 each directly link to these DOFs. If we wished the stage of the design from Fig. 2 to translate along the x-axis, actuators 1, 2, and 3 should be actuated with a magnitude ratio of 2:-1:-1 instead of 1:0:0 as would be the case for the design of Fig. 3.

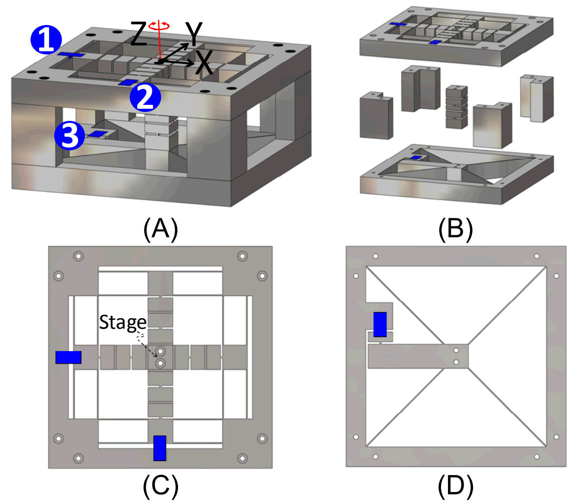


FIGURE 3. Another design (A) with exploded view (B), top piece (C), and bottom piece (D)

SYNTHESIS APPROACH

This section explains how FACT may be applied to the synthesis of decoupled flexure systems. To better understand the principles of FACT, however, we will first analyze the design of Fig. 2 and show how its serial actuation chains not only decouple its actuators, but also act as bearings to guide the stage with the desired DOFs. Figure 4 shows one of these serial actuation chains. The freedom space [1] of its flexure coupling is a single translation arrow along the axis of the actuator. The freedom space of its decoupling flexure is a plane of rotation lines and an orthogonal translation arrow. These freedom spaces are geometric shapes, which represent the DOFs that their flexural elements permit. To determine the total kinematic effect of this serial actuation chain on the stage, we must linearly combine these freedom spaces [1]. The resulting freedom space is shown in Fig. 4B and represents every rotation line on the plane of the flexure blade, every rotation line that is normal to the system's stage as shown by the box of parallel lines, and every translation arrow that points in directions, which are orthogonal to these lines as shown by the disk of arrows in the figure. According to FACT, this freedom space uniquely links to a constraint space, which consists of every parallel constraint line that lies on the plane of the flexure blade and is parallel to the rotation lines in the box of its freedom space as shown in Fig. 4B. If wire flexures were to be selected from this constraint space as shown in Fig. 4C, this new topology would represent the effective constraint that the serial actuation chain from Fig. 4A imposes on the stage (i.e., the topologies of Fig. 4A and Fig. 4C contribute equivalent kinematic/constraint characteristics to the system). Note that if this effective constraint topology of wire flexures replaced every serial actuation chain from the system of Fig. 2, the constraint space for the entire system would consist of every constraint line, which is normal to the surface of the stage as shown by the box of parallel lines in Fig. 4D. This constraint space uniquely links to a freedom space, which consists of all rotation lines that are parallel to the constraint lines as well as all translation arrows that are orthogonal to these lines as shown in Fig. 4E. This conclusion demonstrates that the flexure topology of the system from Fig. 2 does behave as a bearing to guide the stage with the freedom space of Fig. 4E, which contains the three desired DOFs as shown in the figure.

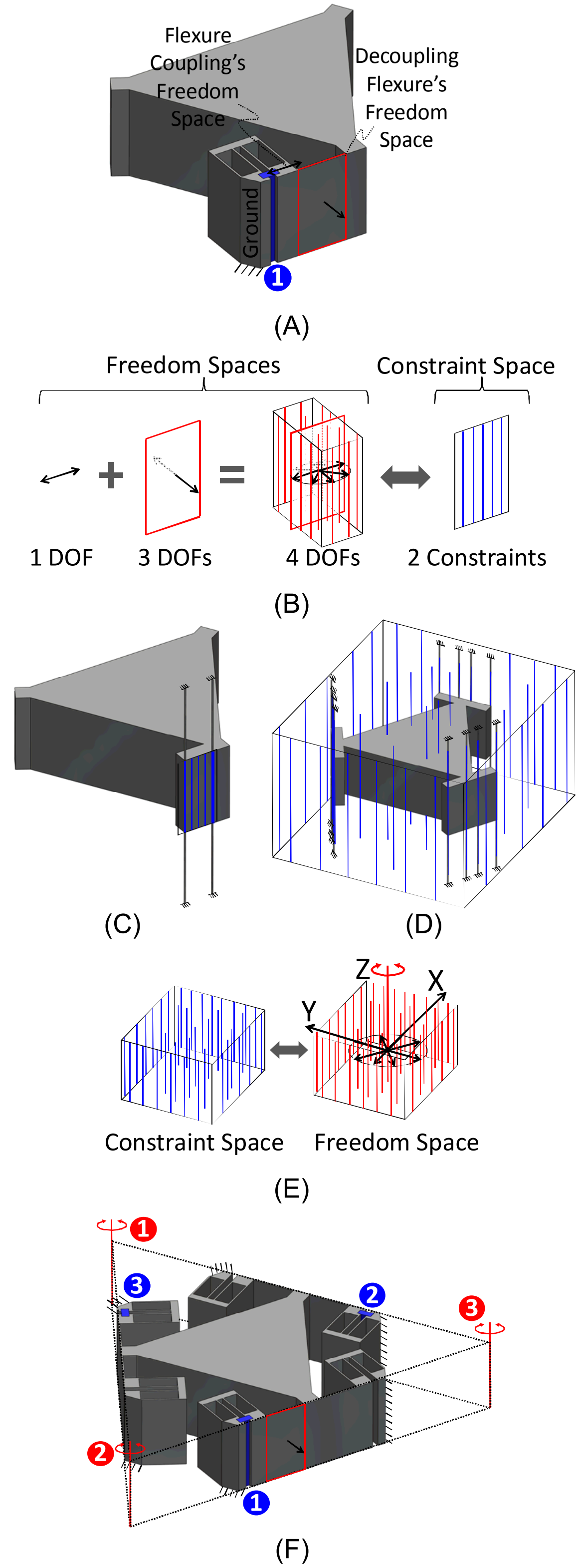
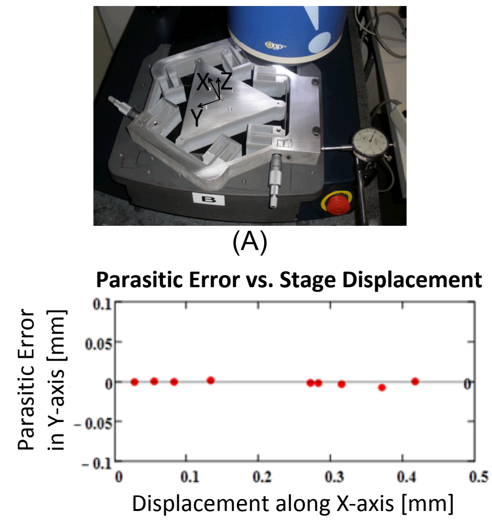


FIGURE 4. Serial actuation chain freedom spaces (A), effective constraint space (B), effective constraints (C), total system constraint space (D), total system freedom space (E), rotation lines lie within planar freedom space (F)

The shapes of FACT may also be applied to confirm that the serial actuation chains are properly decoupling the system's actuators. *If the freedom space of the chain's decoupling flexure contains the motions caused by the other actuators in the system, then the system's actuators will be properly decoupled.* Note that the two rotations caused by actuators 2 and 3 shown in Fig. 4F do lie in the plane of rotations (i.e., the freedom space) of the decoupling flexure pertaining to actuator 1. Note also from Fig. 4A that this freedom space does not contain the translation arrow of its flexure coupling. If this were the case, the actuator would not be able to stiffly transmit its intended motion to the stage.

We are now ready to apply the principles discussed previously to establish the systematic steps that may be used to consider every way any decoupled flexure system may be synthesized using the shapes of FACT.
Step 1: Identify the freedom space that contains the desired system DOFs.
Step 2: Identify the desired motions within that freedom space that are to be actuated and select an appropriate actuation scheme for actuating those motions.
Step 3: Specify the freedom spaces of those actuators and use their constraint spaces to synthesize appropriate flexure couplings.
Step 4: Select effective constraint spaces from within the constraint space of the freedom space selected in Step 1.
Step 5: Select a freedom space that lies within each effective constraint space's freedom space, which *(i)* does not contain the freedom space of its actuator, *(ii)* linearly combines with this freedom space to become the freedom space of its effective constraint space, and *(iii)* contains the motions of the other actuators.
Step 6: Synthesize the decoupling flexures using the constraint spaces of each freedom space from Step 5.

RESULTS
The system of Fig. 2 was fabricated (see Fig. 5A) and tested to measure how well its actuator outputs were decoupled by its flexure topology. An Opg Smart Scope Flash 200 Optical Comparator was used to measure the stage's parasitic errors in the y-axis as it was driven along the x-axis and the results are shown in Fig. 5B. Note that over a range of 0.5mm in the x-axis, the trend of the stage's error in the y-axis is nearly a horizontal line (slope=-0.01 mm/mm) centered close to zero. The small slope of this trend line demonstrates the success of the decoupling flexures.



(A)
(B)
FIGURE 5. Fabricated flexure (A) and data showing coupled drift in an unwanted axis (B)

CONCLUSIONS
The principles of FACT have been adapted to help designers synthesize flexures that decouple displacement-based actuators such that they *(i)* do not impose undesired loads on other actuators, *(ii)* do not affect the outputs of other actuators, and *(iii)* drive the system's stage to move with desired DOFs and minimal parasitic error. Rules have been created for controlling system constraint characteristics (i.e., exact, over, and underconstriant). As a case study, a FACT-designed flexure system was fabricated and tested to experimentally verify how well its flexures decoupled the outputs of its actuators. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-CONF-XXXXXXX.

REFERENCES
[1] Hopkins JB, Culpepper ML. Synthesis of Multi–degree of Freedom, Parallel Flexure System Concepts via Freedom and Constraint Topology (FACT) – Part I: Principles. Precision Engeering. 2010; 34(2): 259-270
[2] Li Y, Xu Q. Design and Analysis of a Totally Decoupled Flexure-based XY Parallel Micromanipulator. IEEE Transactions on Robotics. 2009; 25(3): 645-657