FINAL PROJECT
C162A/C294A: Compliant Mechanism Design

Introduction

DARPA recently requested proposals for Spider-inspired 3D-printing robots, called Self-Propelled Ink Deposition Robots (i.e., SPIDRs), that fabricate complex structures in space by crawling on the web-like constituent struts that they simultaneously print (Figure 1). The inherent flexibility underlying the fabrication approach of these SPIDRs would enable structures of almost any geometry to be made in space for satisfying the requirement of numerous applications and for addressing a variety of unanticipated scenarios on demand (e.g., repairing structures damaged by space debris). Additionally, since the structures that the SPIDRs fabricate consist of ink that is pumped to their deposition nozzles through tethers connected to storage containers (see Figure 1), only the ink would need to be periodically launched into space to replenish the containers once the SPIDRs have already been deployed there. Thus, all required building materials could be brought into space in their most compact, volume-efficient, and shape-flexible form for dramatically reducing the cost of space structures. The automated and swarm-inspired teamwork that SPIDRs leverage would also increase the fabrication speed of such structures, which would reduce their cost further.

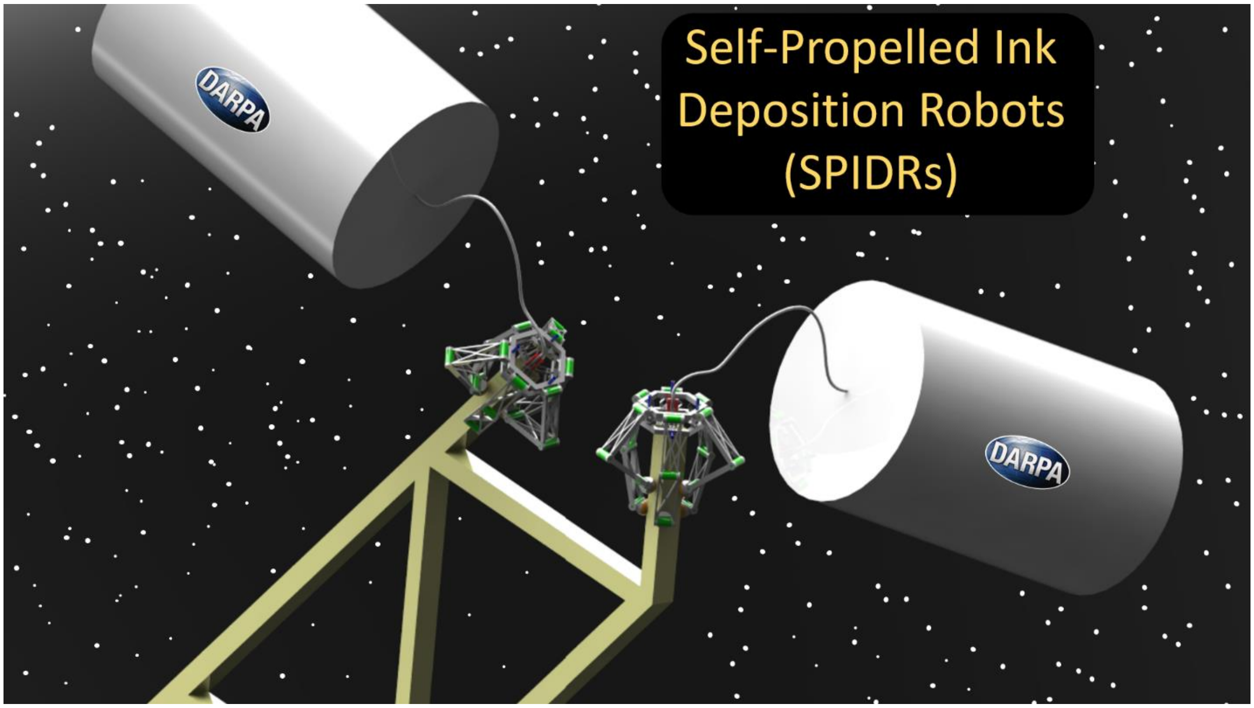

Figure 1. *Two Self-Propelled Ink Deposition Robots (SPIDRs) crawling on the structure that they are simultaneously 3D printing in space. Containers supply the robots with their ink through tethers. The SPIDRs' control circuitry and batteries also occupy a portion of these containers and their wiring is also packaged within the tethers. The containers could leverage solar panels to charge their batteries and would possess small jets to move them so they don't collide or become tangled with anything as the SPIDRs print.*

One of the major challenges currently preventing the implementation of this spider-inspired fabrication approach in space is vibration compensation. It is difficult to 3D print structures with sufficient feature resolution when the nozzle depositing the ink is continually vibrating different and unanticipated amounts in all six degrees of freedom (i.e., three independent translations and three independent rotations) with respect to the structure being printed. Such vibrations are inevitable since the SPIDRs crawl on the structures while their geometry changes as they are printed and as temperatures fluctuate cyclically as the structures orbit.

Thus, although the legs of the robot are responsible for *(i)* raster scanning the printhead so that it can print 3D structures with course resolution and *(ii)* climbing on the structures printed while propelling the printhead in desired directions, precision flexures are required within the printhead to compensate for vibrations in real-time and to achieve fine-resolution printing. Your task is to design the flexures and actuators within the printhead so that the robot successfully achieves this task. Assume that sensing will be achieved by placing brightly-colored spherical fiducials at select locations within the print head so that a high-speed camera can determine the locations and orientations of the bodies within the printhead at any given time. This information will be fed back to the actuators which will drive the flexures that guide the deposition nozzle to keep it stable and help control it's fine-resolution printing capabilities.

Design Requirements

The printhead (i.e., the entire robot excluding its spider-like legs) should fit within a 1 ft^3 volume. This includes its flexures, actuators, structure with fiducials, and deposition nozzle. The actuators in the printhead need to be able to compensate for linear vibrations with amplitudes as large as 0.25 cm and angular vibrations with amplitudes as large as 3 degrees at frequencies between 1 to 10 Hz in all directions. The flexures should be able to survive their deformations without yielding while these vibrations are compensated for. The flexures should be as exactly-constrained as possible and possess as few bodies that are under-constrained as possible. The final design needs to be able to be fabricated using planar processes (e.g., waterjet, wire EDM, machining, etc.) that can produce metal flexure parts, which can be assembled. Finally, note that the position of the deposition nozzle should be controllable with a resolution increment of 0.1 mm or less so that the features that are printed on the structure possess a sufficiently high fidelity.

Task 1: Background

Research previous attempts made by others to print structures in space. Explain how they work and identify their strengths and weaknesses. Highlight how the concept of SPIDRs is advantageous over the other existing approaches.

Task 2: Degree of Freedom Identification

Identify what degrees of freedom (DOFs) your printhead flexures should achieve to compensate for vibrations and enable fine-resolution printing. Be sure to identify where the rotations and/or screws should be oriented and located as well as where the translations should be oriented if such DOFs are identified. Justify why you chose what you did.

Task 3: Flexure Topology Synthesis

Use FACT to generate the flexure topology within the printhead so that the flexures guide the desired deposition nozzle's DOFs selected from Task 2. Be sure to consider exact and over-constraint, under-constraint, symmetry, manufacturability, and thermal stability. Also be sure to consider where the sensing fiducials should be placed as well as how the flexures should be actuated.

Task 4: Actuator Selection

Identify how many actuators you'll need to drive the flexures synthesized in the previous task and what kind of actuators they should be (i.e., linear or rotary). Find actuators from a vendor like Physic Instruments that could drive the desired DOFs over the specified range and with the specified speeds required. Be conservative so that they can easily over perform the specified requirements. Make sure they are sufficiently high-resolution actuators to achieve the system's desired resolution requirements and try to identify the lowest-cost actuators possible.

Task 5: CAD the Final Design

Download CAD models of the actuators you chose from the vendor's website from the previous task and integrate them into your design. Fixture them to the printhead's structure using the instructions provided by the vendor. CAD your designed flexures within the printhead and make sure you optimize the geometry of the flexures and pick their material (e.g., aluminum, steel, etc.) so that they deform over their desired range without yielding. You'll also want to minimize their mass and increase their stiffness as much as possible so that they respond to the actuators' speed with as high a bandwidth as possible. Be sure to also CAD the bolts or other components that constitute the joints within the printhead. Make sure the bolts have the dimensions of real bolts that could be ordered from a website like McMaster (You can download the CADs of the bolts from their website). Clearly delineate how many pieces constitute the printhead, how they are fabricated using planar fabrication processes, and how they should be assembled. Also be sure to CAD the fiducials within the design making sure they are located in intelligent positions to best achieve their task.

Task 6: Finite Element Analysis

Perform a finite element analysis on your final CAD model to demonstrate that all the DOFS achieved by your printhead can be achieved over their intended ranges without any flexures yielding and without exceeding the capabilities of your selected actuators (e.g., load capacity, range, and speed). Perform a modal analysis on your design to make sure the flexures effectively constrain unwanted directions while achieving the desired DOFs with a high enough bandwidth so that the vibrations of the deposition nozzle can be eliminated. Finally, note, you may consider constructing a mass and stiffness matrix of your printhead to optimize its geometry analytically so that the final design achieves all of its design requirements (this is not required but could be very helpful… it could also be extremely time consuming and painful if your design is not simple so don't feel at all pressured to do so). As long as you have a working design, I don't care how you got it as long as you don't cheat by working with others!

Task 7: Report

Write a **brief** report that contains the following items.

(1) Introduction explaining the purpose, importance, and impact of SPIDRs and the need to enable vibration compensation (1-2 paragraphs).
(2) Background information as detailed in Task 1 (1 paragraph and references).
(3) Explanation of your work pertaining to Task 2.
(4) Explanation of your work pertaining to Task 3.

(5) Explanation of your work pertaining to Task 4.
(6) Explanation of your work pertaining to Task 5.
(7) Explanation of your work pertaining to Task 6.
(8) Conclusion

Good luck!