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Creating a High and Homogenous Resolution Workspace for SCARA Based 3D Printers

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Abstract. 3D printing is an additive manufacturing process that has an untold number of applications in fields as diverse as medical prostheses to military vehicle manufacturing not to mention its long term use in component prototyping [1][2]. With the creation of robotic arm based printers, the 3D printing process can be improved in terms of flexibility and time-efficiency, but with the potential trade-off being lower resolution in some areas of printer workspace. To counteract the resolution reduction, we are studying the use of continuously variable transmissions (CVTs) coupled to the robot's traditional revolute joints [3]. This paper will show that CVTs allow our SCARA-based robotic printer called DEXTER to achieve a resolution as good or better than a traditional desktop style 3D printer.

Keywords: Selective Compliance Assembly Robot Arms (SCARA), Spherical Continuously Variable Transmissions (SCVTs), 3D Printer Resolution, Dexter, MATLAB.

1. Introduction

1.1 Gantry 3D Printers

3D printing is an additive manufacturing (AM) process that builds customized parts layer-by-layer based on a computer-aided design file. The most common 3D printer configuration is a gantry-style or "H-frame" system. These printers use a set of orthogonal linear bearings to precisely position the extruder along the x and y axes of a print bed that may be raised or lowered. One benefit of a gantry style printer is that the extruder's workspace has a homogeneous resolution; meaning the smallest movements the extruder can make is consistent and independent of its position in the x-y plane. This characteristic results in a print resolution that can be maintained throughout the part. Building a homogeneous resolution printer with two or more independent extruders would enable the efficient printing of parts that contain unique material combinations including conductive materials within the layers [4]; however, H-frame and other parallel linkage configuration printers preclude the use of collaborating extruders (or other tools) without collision.

1.2 SCARA 3D Printers

Dexter, our prototype ambidextrous, multipurpose machine, has two SCARA (Selective Compliance Assembly Robot Arms) manipulators as shown in Figure 1 [5]. Each arm is made up of two links connected by two revolute joints. The base of the upper link is able to move vertically giving Dexter's extruders 3-degrees-of-freedom.

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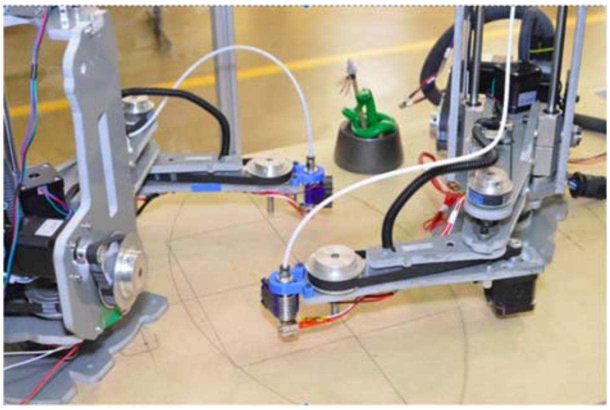

Figure 1. Dual SCARA 3D Printer "Dexter"

Dexter'sindependentroboticarmsprovidethedexteritynecessaryforcollaborativeandcollision free 3D printing and promise a host of benefits to traditional AM. For example, if each robotic arm is equipped with an extruder a part can be printed in nearly half the time. Or each extruder could print a different material, thereby facilitating the simultaneously integration of components that require unique substrates. Finally, a second arm could be equipped with a traditional tool permitting subtractive operations (e.g.: milling and sanding) to be done in tandem with the additive build process [6]. In short, Dexter's multi-SCARA configuration has the ability to greatly improve the capability and speed of AM.

The bases of Dexter's arms are located such that the arms' shared reach or workspace is maximized, and the motion of each set of arm links is controlled to avoid collision [7]. Like other 3D printers, Dexter's joints are controlled by stepper motors, an electric motor that moves in increments, or steps. Popular desktop style 3D printers use stepper motors with 200 steps per revolution. The stepper motor controller can increase that base number of steps through a process called microstepping resulting in extruder resolutions of 11 microns (0.0004 inches) like that of the MakerBot Replicator 2 [8]. However, the combination of links and stepper motors result in Dexter having a lower print resolution than traditional 3D printers, especially when one of its arm is outstretched. Consider that Dexter's stepper motors rotate its joints which in turn change the position of the links. To determine resulting extruder resolution ΔX_{res} the maximum steeper motor or joint esolution $\Delta\Theta_{res}$ must be multiplied by the manipulator's Jacobian J. The Jacobian matrix relates changes in joint velocities to tip of the arm velocities in Cartesian coordinates,

$$\Delta \mathbf{X}_{res} = \mathbf{J}\left(\boldsymbol{\Theta}\right) \Delta \boldsymbol{\Theta}_{res} \tag{1}$$

Insomelocationstheelementsofthe Jacobianbecomequitelarge,especiallynearthe boundaries of the workspace, such that the smallest extruder motion is many times that of other locations. This change in positional accuracy is true for all articulated manipulators but is exacerbated by the use of stepper motors which have lower positional accuracy than the servo motor systems used in most manipulator systems.

1.3 Spherical CVTs

To improve Dexter's resolution, we are studying replacing its stepper motor joints with a spherical continuously variable transmission, or SCVT. The SCVT is a nonholonomic transmission based on rolling contact [9]. As shown in Figure 2, a SCVT consists of a sphere caged by four rollers: two drive rollers on top of the sphere and two steering rollers underneath and inside a bevel gear set for this particular SCVT.

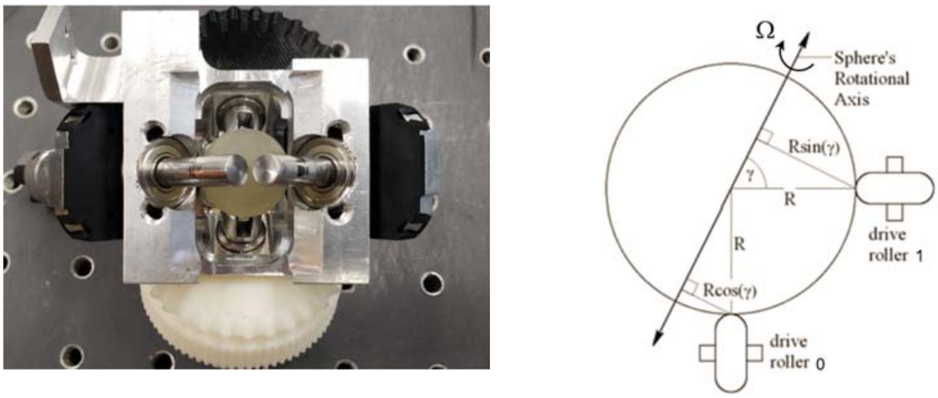

Figure 2. Left: SCVT with 0.5 in. sphere, drive roller shafts and steering roller gears. Right: Plane of the SCVT rotational axis which contains sphere's center and the contact points between sphere and drive rollers.

The sphere transmits angular velocity from one drive roller to the other at a ratio $\omega_1 : \omega_2$ determined by the sphere's transmission angle γ. The transmission angle is determined by adjusting the orientation θ of the steering rollers according to the following equation,

$$\frac{\omega_1}{\omega_0} = \tan(\gamma) = \frac{\sqrt{2} + \tan(\theta)}{\sqrt{2} - \tan(\theta)} \tag{2}$$

The SCVT transmission ratio is continuously variable up to a maximum goverened by friction. In practice we have achieved transmission ratios of nearly 6:1.

Using two SCVTs, our goal is to couple drive roller 1 from each SCVT to one each of Dexter's two joints. The second drive roller (drive roller 0) from each SCVT will be coupled to one another and driven by a stepper motor. Through computer control of both SCVT steering roller angles we can maintain any desired angular velocity ratio between Dexter's joints, thus permitting any desired extruder motion direction. The SCVTs provide for joint motion infinitely smaller than that of Dexter's original joint motors resulting in smoother nozzle paths and high resolution while still using a stepper motor input common to most 3D printers.

The objective of the present work is to show how SCVTs can be used in place of standard robot joints to increase the resolution of Dexter. This work will also investigate how resolution is affected through the increase of stepper motor steps for a traditional SCARA manipulator.

2. Experimental Methods

To investigate the effect of SCVTs on the resolution of a SCARA manipulator,MATLAB simulations were utilized in order to plot and compare the resolution graphs of Dexter using standard steeper motor joints to the resolution graphs of Dexter using SCVTs. In addition, multiple traditional SCARA simulations were run showing the effect of an increasing stepper motor steps per revolution.

Generally, to 3D print a part layer software is used to transform a CAD file into g-code which tells the printer nozzle where to move, how fast and at what temperature to heat the filament. We used MATLAB to read the g-code for a 'Calicat' part, a standardized file used for 3D printer calibration, and plot what would result if the output was sent to an actual 3D printer. The 'Calicat' plot in Figure 3 was simulated using approximately a 100x100 mm task space in MATLAB with a feed rate of 100 mm per minute. The program evaluated each line of the g-code, and plotted them as corresponding line segments in a Cartesian coordinate system which could be considered the build plate of a 3D printer.

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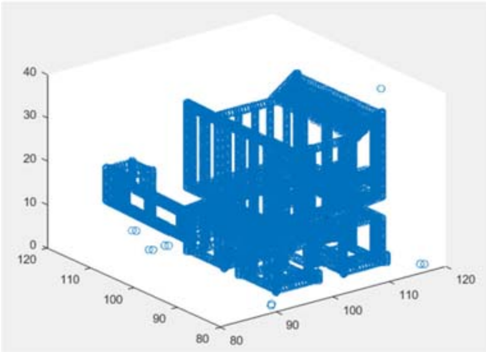


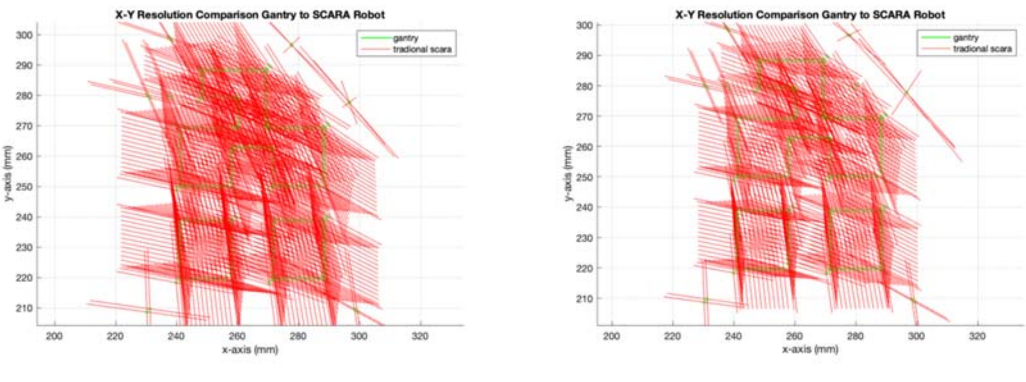
Figure 3. Calicat Plot

To visualize the effect of different resolution values, a single layer of Calicat was graphed in MATLAB assuming the nozzle was at the end of a 2-link SCARA-based 3D printer. Each link had a length of 203.2 mm and the base of the first link was attached to the origin of a x-y workspace. The robot's two joints were equipped with a 200 steps per revolution stepper motor. As the simulated nozzle followed the motion dictated by the g-code, the SCARA's inverse kinematics were used to calculate the change in joint angles for a given change in Cartesian nozzle position. These angle changes were subsequently interpolated to conform to the smallest possible joint angle change according to the available stepper motor steps.

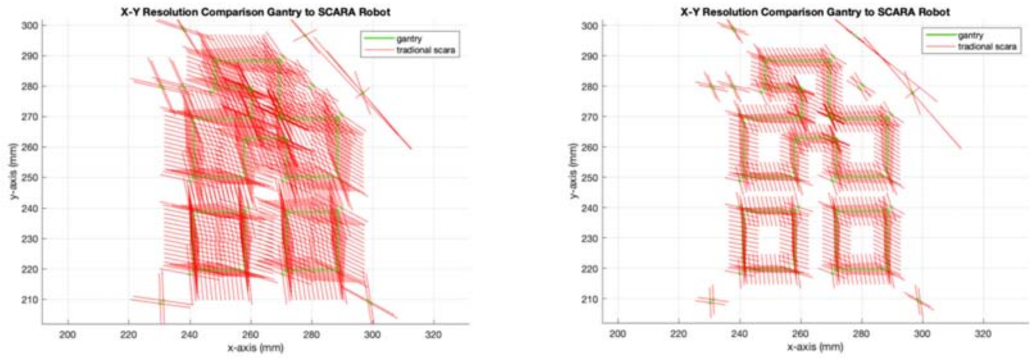
The program graphs ellipses along the segment boundaries of a desired layer of the Calicat. The major and minor axes of each ellipse represents the resolution or minimum x and y-axis motions at that location for our example gantry style printer with a 11 micron resolution. A gantry printer has a homogeneous resolution so the major and minor axes of the resolution ellipses are everywhere equal forming circles. Finally the program graphs axes lines representing the resolution of the SCARA printer at the center of each circle graphed in the prior step. If the resolution of the SCARA printer is the same as the gantry printer then the lines will be contained within the circles printed previously. If the resolution is worse the lines will proceed outside of the circles and may not be parallel to the x and y-axis. These program steps were repeated three times for an increasing number of microstpes.

3 Results and Discussion

WesimulatedprintingtheresolutionellipseswithaSCARAbasedmanipulatorwitheithertraditional stepper motor joints or with SCVT equipped joints. For the traditional stepper motor cases we assumed a varying number of microsteps for the stepper motor. The first test was done with 16x microstepping resulting in a minimum joint rotation of 0.1125 degrees. Three additional simulations were done for 24x, 32x, and 64x microsteps resulting in minimum joint rotations of 0.075 degrees, 0.056 degrees and 0.028 degrees respectively. Next we performed a simulation with the SCVT equipped SCARA.



(a) 3200 Steps per Revolution (c) 6400 Steps per Revolution



(b) 4800 Steps per Revolution

(d) 12800 Steps per RevolutionFig 4: Traditional SCARA Resolutions

Figure 4. Traditional SCARA Resolutions

3.1 Traditional SCARA Robot

According to the plots in Figure 4, a SCARA based 3D printer with standard stepper motors will result in much worse prints than is possible with a gantry-style printer like the Makerbot Replicator 2. The CalicatlayerresolutiongraphsimulatedusingaSCARArobotwith0.1125degreesminimum joint rotation (3200 steps per revolution) is shown in Figure 4a. The lines representing the major and minor resolution axes are very much longer and outside of the gantry resolution circles and not at the correct orientation. A SCARA with low resolution joints cannot produce perfectly horizontal or vertical lines at every location within its workspace. As the microstepping increases to 64x in Figure 4d, the ability to print improves drastically. There remains orientation error, especially at the distances furthest from the origin. As mentioned during the discussion of Equation 1, at these locations a SCARA based printer has non-homogenous resolution meaning that the smallest possible axis motions are dissimilar and along axes that may not be orthogonal.

As the microstepping increases, the lines on each plot became more contained, meaning that the resolution is improving and becoming closer to that of the gantry style 3D printer. However, it is important to note that higher microstepping is itself a control issue, often resulting in increased resolution but decreased accuracy.

3.2 SCVT-SCARA Robot

Upon using SCVTs at each of the SCARA's joints, the resolution increased dramatically. The size of the resolution axes in Figure 5 shows a many times improvement than even the best traditional SCARA plot that was shown above. The resolution also proved to be homogeneous in the x and y directions. Fromtheplot,itcanbeobservedthatnearlyalloftheprintlinesfromtheSCVTequipped SCARA printer were contained within the circles that represent the homogeneous resolution of the example gantry printer at each location, with the exception of the anomaly in the far-right corner which would be the farthest extension of the SCARA arm where nozzle motion is not possible in an arbitrary direction.

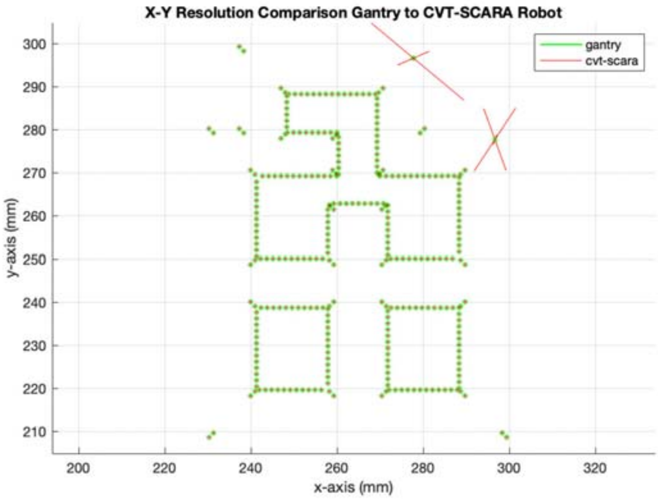


Figure 5. SCVT-SCARA Robot

4. Conclusion

The use of nonholonomic SCVTs improved the simulated print resolution of Dexter to many times that of a SCARA robot with traditional joint motors. The resolution also increases in homogeneity. Thus, usingSCVTscreatesthepossibilityofaSCARAbased3Dprinterwithgantryprinterextruder resolution while still using a stepper motor input.

For future work, we anticipate designing a SCARA based 3D printer with SCVT equipped joints. We are also interested in determining if a SCVT equipped 3D printer will excel at printing smooth curvature line segments.

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