Design and Construction of a 6-DoF Fabrication Platform

James Grossman, Warren Parad, Hod Lipson
Mechanical & Aerospace Engineering, Cornell University, Ithaca NY 14853, USA

Abstract

This research demonstrates a working freeform fabricator with a six degree of freedom print-head capable of additive fabrication onto existing structures. A parallel actuation mechanism was developed with stationary motors. Kinematic simulations of the printer's motion were used to analyze and optimize the design. The components of the printer are described, including the control system and print head mechanism. A working fabricator was then constructed and tested. An additive three dimensional structure is demonstrated and the accuracy and reliability of the printer is analyzed.

Goals and motivation

The goal of this project is to create a printer capable of additive construction onto existing parts or structures (Figure 1). While there are many types of three dimensional printers that are capable of building a part from scratch layer by layer, there has been relatively little work done on printers with the adaptable print-heads and robust control mechanisms necessary to print onto an existing surface. Existing bodies of work tend to focus on regular planar deposition systems with a built-in CNC component allowing for out of plane removal (e.g. [12]), although there have been successful attempts at parallel mechanisms for subtractive assembly (e.g. [4,11]). There are many uses for such a device: In order to perform touch up or repair work, as well as for augmenting existing parts (e.g. [1]). A flexible build platform can help prevent damage to existing parts and achieve an optimal angle for deposition of material for better functional performance. It is also advantageous to be able to print *in situ*, especially when the site is not normally accessible (e.g.[3]).

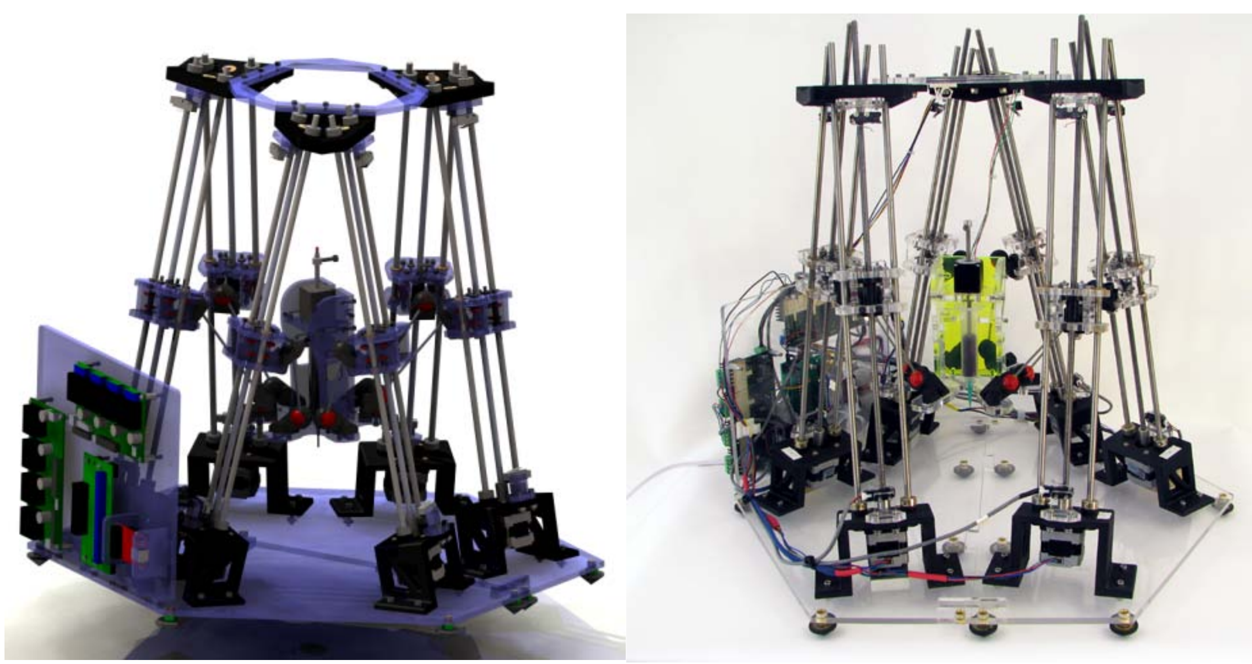


Figure 1: Completed Printer: CAD model (left), actual printer (right)

A secondary goal of this project is to investigate printer systems with parallel actuation. Parallel actuated systems are ones in which the motors that control the system are independent; these motors are fixed in place and do not move during operation of the device. They provide a better tolerance than serial actuators, since an error in one rail will not necessarily affect the other rails, whereas on a serial mechanism such errors accumulate. Parallel mechanisms are known for their rigidity but sometimes suffer from severe nonlinearities and singularities.

The fundamental architecture of additive manufacturing technology used today has not evolved substantially since their inception. The majority of rapid prototyping platforms use a three degree of freedom print head that follows the Cartesian coordinate system. These printers are capable of moving in the *x*, *y*, and *z* directions, but are unable to control the pitch, yaw, or rotation of the print head. A six degree of freedom print head would provide an increased level of control, making it very useful for in-situ printing, e.g. work on biological systems where the substrate extruded by the print head needs to be placed in exactly the right position and orientation.

Method/ Technical Approach

There is a significant body of work on analysis and control of parallel manipulators. The majority of technical papers reviewed detail the analysis of analogous systems such as a Stewart platform (e.g. [2,5,10,9,6]). These methods are based on analysis the forward kinematics of the platforms, which describe the position and orientation of the platform given the lengths of the actuators. This is considerably simpler than inverse kinematics, which requires the calculation of the actuator lengths based on the desired position of the platform.

We used a relaxation-based approach to perform the inverse kinematics [7]. Starting with a given target print-head position and orientation, we mathematically relax the actuator positions until they reach in equilibrium. This relaxation process is then repeated for multiple points along a desired path of the print head, yielding the required trajectory of the actuators for that path.

A critical challenge in the design of a parallel actuator is its sensitivity. Because of the nonlinear transfer function between actuators and the end effectors, some regions may be very sensitive to actuator perturbations (high gain), while other regions may be insensitive to actuator positions (uncontrollable), required discontinuities, were entirely unreachable (dead zones), or were undefined (singularities). Using the relaxation process, we could determine, for each point along a path, the sensitivity of the print-head's position to perturbations in the actuator positions. This calculation yielded a sensitivity score that could serve as a figure of merit for the quality of a given design (configuration of motor positions and rail orientations). To this end a series of scripts were written that could be used to easily tweak the basic design parameters of the printer, such as the length of the rails or the shape of the base, in order to determine which combination of shapes and lengths results in the most stable design. Stability in this case is defined as the ability to duplicate a given design within a margin of error and a reasonable time frame. To achieve stability the final printer design must minimize any internal singularities and be geared towards producing a wide variety of basic geometric paths and shapes in the largest build space.

Once the basic design parameters have been optimized, we developed a three dimensional model of the printer that represented the layout and dimensions of the components. As construction progressed the original model was updated to take into account minor changes that were made. Several of the drive components, as well as the print head and rails were based on the Fab@Home system [8].

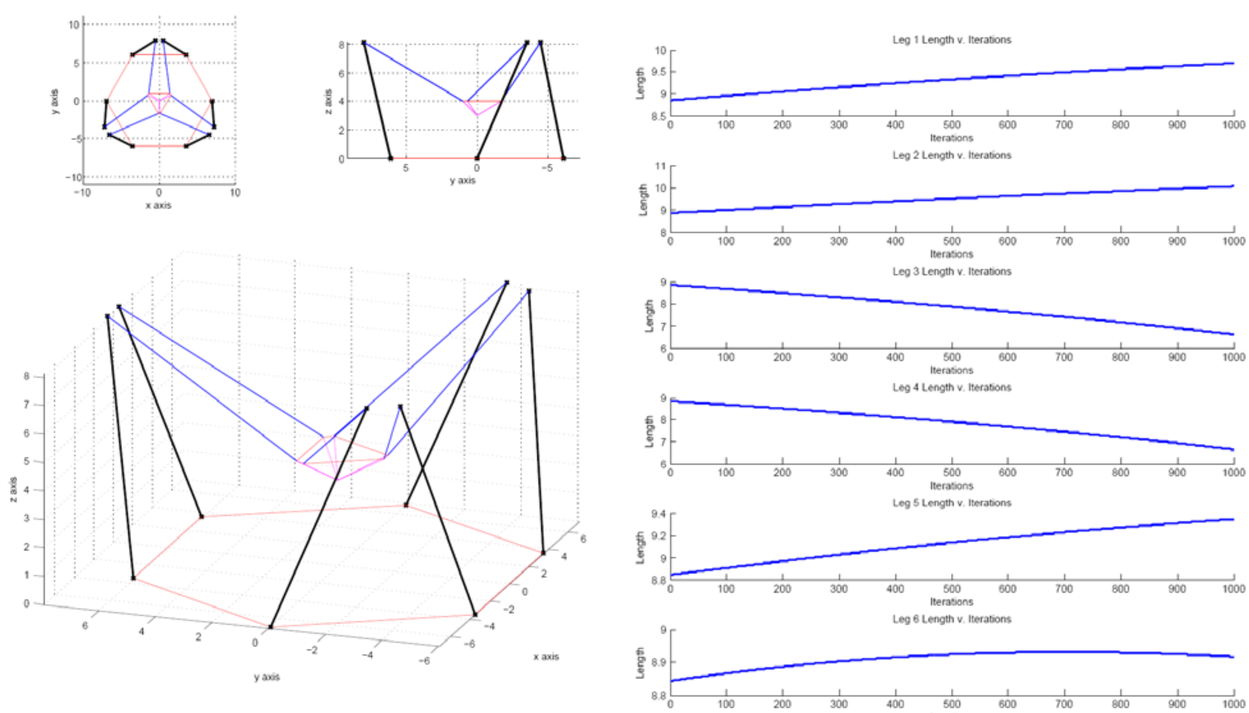
Testing of the printer involved execution of paths using the printer of increasing complexity in order to demonstrate the full capabilities of the device. Dry printing runs of basic three dimensional shapes were attempted and the results were documented.

Implementation and Results

We used a bruit-force search to explore the space of parameters relating to the shape of the base, middle, and top of the printer as well as the length of the rails and arms and the overall diameter of the various levels of the printer. Using these dimensions as parameters the program attempted to draw a predetermined shape by relaxing the lengths of the rails.

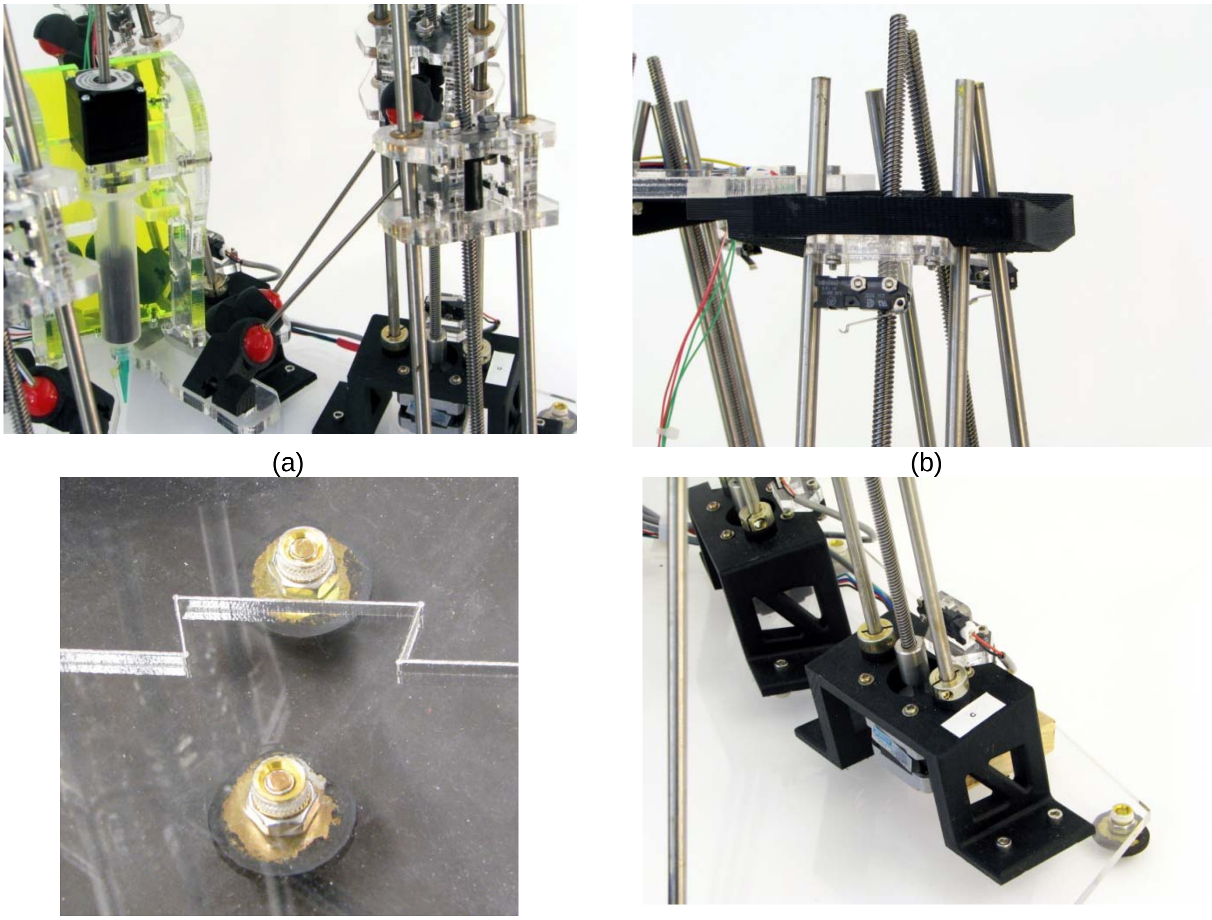
After each run, the program provided the values of the various design parameters changed during each iteration, the amount of time that it took to produce the completed target path and a number relating to the accuracy of the final path compared to the desired path. Since the design space was so large owing to the number of components that could be modified, we manually identified trends in order to avoid groups of possible designs that were exhibiting large number of internal singularities or other adverse features.

Figure 2 shows the kinematic model and resulting convergence curves for a search process for a configuration where the leg changes needed to create a design did not require any instantaneous shifts. Another script was written that calculated the lengths of the arms required to reach every point in the design; this script also tested the provided design to make sure that none of the points exceed the arm length specified. Unfortunately, the accuracy required for this project meant that the synchronous version of the relaxation algorithm was needed; this proved to be the largest performance bottleneck on the tests, though the effects were minimized by dividing the calculations over several computers.



(a) (b)

Figure 2: Design optimization process and final optimized design: (a) kinematic model (b) convergence of rail lengths



(a) (b) (c) (d)

Figure 3: Construction details: (a) the print-head (green) connected to the six rails using ball-and-socket links; (b) top of the rail; (c) Butterfly Tabs: These butterfly tabs keep the two base pieces aligned and the thermoplastic inserts with feet keep the printer level; (d) Bottom of the rail

The next step in this project was designing a CAD model of the printer. We used 6mm acrylic sheets and 3D printed ABS plastic parts to form the frame of the printer, with connections and offsets comprised of various steel and brass components. The design model was divided into six sections: the base, the rail system, the travels for the rail, the top connecting plate between the rails, the electronics board and the print-head itself (adopted from Fab@Home).

The base section was comprised of two acrylic sheets joined together with a butterfly-tab and acrylic locking system (Figure 3c). Once the parts were cut out, thermoplastic inserts were placed into the base so that rubber feet could be screwed onto the bottom. These feet allow the base to be adjusted so that it is level as well as protecting the acrylic from the surface that the printer is resting on. Additionally, the rubber feet act as vibration absorbers, preventing minor vibrations on the table from affecting the printer and vice-versa.

Directly onto top of the base is the rail system for the printer. The rail comprised six identical ACME threaded rods connected to stepper motors and mounted on ABS plastic frames. The frames orient the motors in the correct direction while also providing a base for the support rods, which help guide the travel sections up and down the rails. Figure 3 shows the rail system (Figure 3a), the bottom anchor with motor (Figure 3d) and the top anchor (Figure 3b). One of the main issues that arose with these parts was the tolerances of the printed ABS plastic and the connections between it and the stepper motors. This issue was eliminated by drilling out the existing mounting holes in the ABS plastic so that the bolts holding the motor could be connected without straining or deforming the part. The precision steel support rods were attached to this frame using a combination of mounting holes and shaft collars that sit on either side of the plastic mount, preventing the rods from sliding (see Figure 3d). The final component of the rail system is the attachments for the limit switches on the top of the mounting frame (shown in Figure 3b). These switches are connected to the electronics board and prevent the stepper motor from pulling the travel too close to the base.

The travel is the device that connects the rails of the printer to the print-head itself (bottom-left of Figure 3a). The design of the travel was one of the first parts finished for this printer, and the limitations on its size helped to determine the dimensions for the rest of the parts. The travel is constructed from acrylic sheets held together with a combination of press-fit joints and the tab-notch system used on the Fab@Home printer. Additionally, the travel includes oil impregnated brass bearings and a plastic threaded nut and flange assembly which connect to the support shafts and the ACME rod respectively. The connection to the print-head is done by a custom built ball and socket joint that is attached to the front of the travel. This joint is made from rapid-prototyped ABS plastic socket into which a 20 mm bead is press fit (see red beads in Figure 3a). This bead has a thermoplastic insert melted into it, allowing a threaded rod to be attached between the sockets on the print-head platform and the ones of the travel, forming the ‘arms’ of the printer.

To prevent the rail system from vibrating during operation the printer also incorporates a top plate that connects the rails together allowing them to provide structural support for one another (seen in Figure 3b). This top plate was not part of the original model of the printer, and it proved to be the most difficult component of the printer to design due to the irregular angles between the top of the rails. The plate is comprised of three ABS plastic parts that bridge the gap between the adjacent rails and an acrylic sheet that connects these components to one another. The bridging parts also have low friction ball bearings on them to reduce the friction between the ACME rods and the ABS plastic, as well as shaft collars around the rail’s steel support rods to prevent the top plate assembly from slipping. Finally, the top plate contains mounting brackets for limit switches to prevent the travel from impacting the top of the printer.

The control system for this printer is similar in form to the system for the Fab@Home Model 1; it is comprised of stepper motor amplifier boards connected to a microcontroller board with header connections and a USB port, allowing the system to be controlled by any modern computer. These components are mounted onto an acrylic board with standoffs to allow for air flow around the parts, and the whole board is mounted vertically on one side of the printer’s base. To ensure that the board does not fall over, support struts made from acrylic provide additional connections between the base of the printer and the back of the electronics board.

The final component of the printer is the print-head itself (Figure 3a). This part is comprised of a slightly-modified syringe tool mount from the Fab@Home system which is attached to a custom acrylic base. Similar to the travel section, this base provides the connections between the print-head and the arms of the printer which are in turn attached to the travel and rail systems. In order to get the best range of motion out of the ball and socket joints on this base there are acrylic offset pieces that hold the ball joints at specific orientations to avoid lockups in the arms or collisions between two arms. Ideally the print-head should be as light as possible to reduce the strain on the rails system. As such one goal when designing this part was to reduce the weight as much as possible. The main weight comes from the stepper motor used to extrude material through the syringe tool; however effort was made to cut out as much acrylic as possible from the attachment plate.

After the printer was assembled, tests were performed in order to ensure that the physical system matched the simulated results. These tests included executing free form paths with and without a syringe attachment, demonstrating the capability to move in a controlled manner through all six degrees of freedom and small print tests in which the ability to deposit onto an inverted sphere was demonstrated. Next, tests were conducted to determine the accuracy of the system. The first test involved printing straight lines on wax paper. The linearity of these lines was then determined using a first order polyfit function in MATLAB using the center points of the lines as the experimental data. While straight lines are trivial for a gantry system, they are as difficult for a parallel system as any other curve. Linearity therefore serves as a good test of system precision.

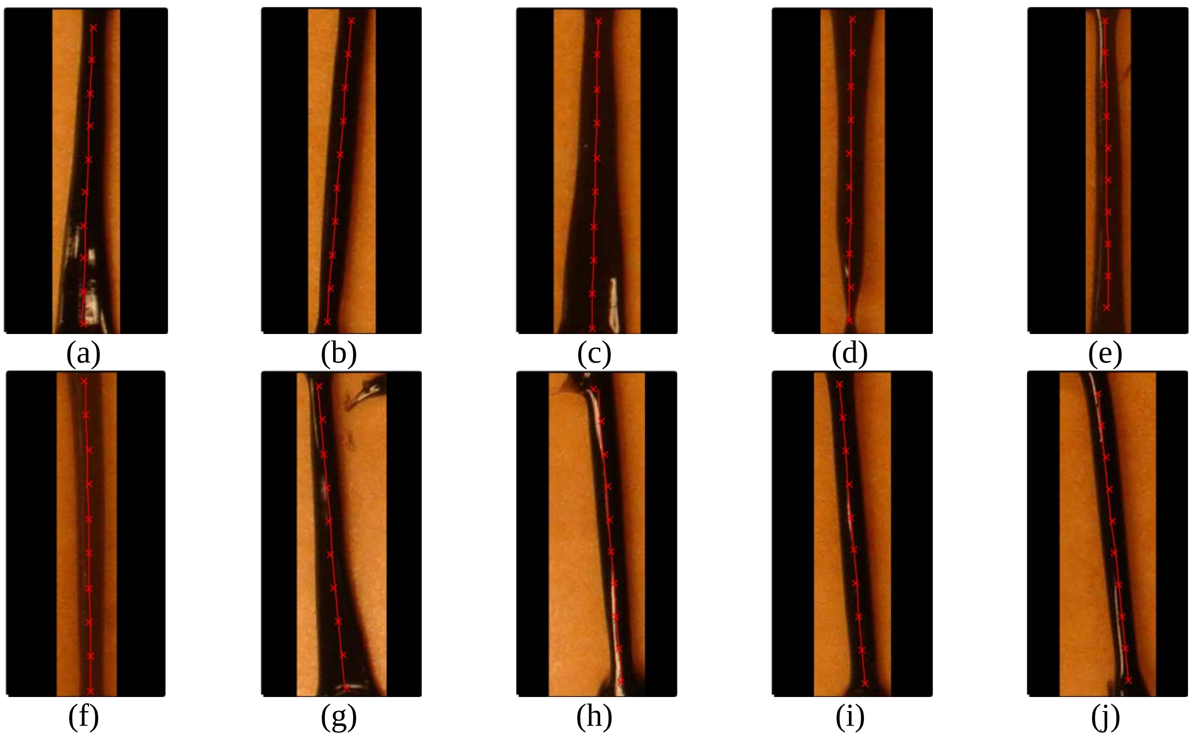


Figure 4: Straight line test results. Images were cropped and rotated; best fit lines were calculated and placed by MATLAB.

Line	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
Variation (mm)	0.37	0.25	0.24	0.31	0.41	0.55	0.83	0.82	0.17	0.25
R^2 value	0.9518	0.9964	0.9538	0.5630	0.6083	0.7268	0.9693	0.9522	0.9986	0.9980

Table 1: Average variation from mean in mm and R^2 values of best fit lines.

The accuracy of the lines was measured by calculating the average variation from the mean, and the r-squared values of the fit. The results are summarized in Table 1; with an average deviation of 0.42±0.075 mm and a mean R^2 value of 0.87±0.05.

Figure 5: System test: (a) Complete structure test: A silicone-based caulking material was used to form a cube on top of an existing hemisphere; (b) Reliability Test: The hash marks are 1/64” apart.

The tests were performed using a syringe deposition tool filled with a silicon based tile sealant. The varying thickness of the lines is caused by the inaccuracies in the manual control of the syringe plunger. Target length for the lines was 1.5 inches – this was fairly close to the actual length; the images above show that the lines generally fit in this dimension with only a little creep due to the syringe tool at either end of the line.

The printer’s ability to fabricate a three dimensional structure was tested by printing an open ended cube onto a hemisphere formed from half of a ping-pong ball (Figure 5a). The test was performed by manually instructing the printer to follow a series of parametric coordinates that defined a rising square pattern, while taking into account the curvature of the hemisphere. This allowed the printer to form the cube in a single print operation.

A repeatability test was also performed to determine the printer’s ability to place dots on a sheet of paper in a repeatable fashion. The test involved placing two dots one inch apart on a flat surface thirty times in a row. The dots were made by a pen mounted in the syringe tool attachment with the results shown in Figure 5b. The dot in the center of the image is a test dot demonstrating the size of the dots made in the run. As the image shows, the print-head demonstrated a regular precession during the test that prevented it from placing the dots exactly on top of one another. However, since the distance between the dots remained constant during this test the precession was likely due to the slight deflection to the print-head caused as the dots were placed. All these tests were done using open-loop control. We expect that higher precision could be attained using closed loop system.

Conclusion

The purpose of developing a six degree of freedom rapid prototyping platform is not just to expand the design space of rapid prototyping machines, but to create a printer that is capable of more than the current state of the art. The printer detailed above is capable of drawing arbitrary three dimensional shapes through the use of a rotating and translating print-head. The use of a parallel actuation system to drive the printer demonstrates this platforms use in the free form fabrication field.

Acknowledgements

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References

1. Chung M., Malone E., Tolley M. T., Chepaitis A. J., Lipson H., (2008) “Object Augmentation for the Visually Impaired Using RP”, Proceedings of the 19th Solid Freeform Fabrication Symposium, Austin TX, Aug 2008
2. Dafoui, El-Mouloudi, (1998) “Analysis and Design of a Six-DOF Parallel Manipulator, Modeling, Singular Configurations, and Workspace”, IEEE Transactions on Robotics and Automation, Volume 14, No. 1
3. Grenouilleau J. C., O. Housseini, and F. Pérès., (2000) “In-Situ Rapid Spares Manufacturing and Its Application to Human Space Missions”, Proceeding of Space 2000, p.42-48.
4. Jongwon Kim, Chongwoo Park, Sun Joong Ryu, Jinwook Kim, Jae Chul Hwang, Changbeom Park, Iurascu, C.C., “Design and analysis of a redundantly actuated parallel mechanism for rapid machining” , IEEE Transactions on Robotics and Automation, August 2001, Volume 17, Issue 4, p. 423-434.
5. Kang, Ji-Yoon, (1996) “Robust Tracking Control of Stewart Platform”, Proceedings of the 35th Conference on Decision and Control, Kobe, Japan, December 1996
6. Lazard, Daniel, “The (true) Stewart Platform Has 12 Configurations”, IEEE 1994
7. Lipson, H., (2006) "A Relaxation Method for Simulating the Kinematics of Compound Nonlinear Mechanisms", ASME Journal of Mechanical Design, Volume 128, Issue 4
8. Malone E., Lipson H., (2007) “Fab@Home: The Personal Desktop Fabricator Kit”, Rapid Prototyping Journal, Vol. 13, No. 4, pp.245-255
9. Masuda, T., “Specific Kinematic Changes in a Linear-Actuated Parallel Mechanism According to Differences in Actuator Arrangement”, Proceedings of the 2000 IEEE/RSJ Internal Conference on Intelligent Robots and Systems
10. Merlet, J. –P, “Solving the Forward Kinematics of a Gough-Type Parallel Manipulator with Interval Analysis”, The International Journal of Robotics Research 2004, Volume 23, No. 3
11. Petko, M., Karpiel, G., “Mechatronic Design of a Parallel Manipulator for Milling”, 2005 Proceedings IEEE/ASME International Conference on Advanced Intelligent Mechatronics., p.759-764
12. Weiss, L. and Prinz, F., 1998, "Novel Applications and Implementations of Shape Deposition Manufacturing,” Naval Research Reviews 1, Office of Naval Research