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A RECONFIGURABLE SYSTEM TO ENHANCE THE WORK ENVELOPE OF A SOLID FREEFORM FABRICATION SYSTEM

Rajeev Dwivedi*, Ayush Sinha†, Pranav Ebburu†, Yash Saxena** , Shabab Haque*†, Shaunak Kulkarni†

*TechKARMA LLC, Plano TX, Corresponding Author rajeev@satkriti.com

†Frisco ISD, Frisco TX , **Plano ISD, Plano TX , *†Allen ISD, Allen TX

Abstract

Size and aspect ratio of parts created by Solid freeform fabrication systems is limited by the configuration of equipment. Also referred to as Axes, the maximum reach of material deposition end effector determines the maximum size of the part that can be built. Inherent to most the SFF system is the drive configuration that limits the extent of the reach of the end effector. This paper proposes an alternate architecture that overcomes the drive limitations and hence provides an ability to enhance the work envelope. Two systems proposed include – (1) Cartesian axis stacking and (2) Common Vehicle arrangement. The system drive may be built such that multiple units can be combined and reconFigure d to expand the total work envelope.

Introduction

Shape and size of the parts manufactured by Most of the Solid Freeform systems also referred to as the 3D printing equipment is limited by work envelope of the System. Despite being a general purpose manufacturing system most of the 3D printers are built not to exceed 1ft Sq. cube of work envelop [1, 2, 3]. A sector wise survey[4] of the usage of 3D printing(also referred to as Additive manufacturing) accounts for Industrial/business machines - 10.8%, Medical/dental - 15.1% Consumer products/electronics- 33.6%; cumulatively about 60%. These industries are small form factor intense. Additionally, within the consumer sector and hobby market most of the products sold do not exceed 600mm [6].

Recently many 3D printers have been introduced in the market that can print, on demand, larger objects. This includes Strasys[4], Norsk Titanium (NTi) , ExOne, voxeljet, EBam, etc. However such printers are specialty application such as mold-making, and in many of the instances for repairs. Such systems are extremely expensive. Additionally the architecture of the system is fixed and has large size envelopes. Subsequently such systems have much larger drives, are complex and more expensive. Any organization or institution acquiring and investing into getting such a dedicated system should be able to justify the cost with the production/usage requirement.

Inherent to the size is the ability of mechanical and electrical drives and ensuing dimensional accuracy. Enhancing the size of the machine translates into skewing of the aspect ratio of the

drive dimension and hence stacking of errors. This paper is an attempt by a group of middle and high school students to create a cheap reconfigurable 3D printing system that can be scaled on need basis. Core of the effort lies in sustaining the simplicity offered by popular 3D printing architecture. To the benefit of the hobby community, enthusiasts and researchers, there is an insistence on keeping the cost low. The controls implemented are easily scalable.
The development of the system is done within the framework of replicating rapid prototype also referred to as RepRap [13,14,15]. The availability of cheap hardware, knowhow, and hobby community resources has been instrumental in conceptualizing, deploying ad testing various concepts.

Initial part of the paper describes different ideas that are considered. Pros and cons of the same are evaluated. The paper describes two primary architectures that were pursued. A detailed description of the same follows. The paper concludes with the results and future work

1 . Spatial manipulator Architectures in 3D printing

A Solid Freeform Fabrication system manufactures part by layered deposition of material. Also described as 2-1/2 axis approach, layers of material are deposited in a sequential manner. Such a system comprises of two primary units this includes: (1) Spatial manipulator (2) Material delivery end effector unit. The spatial manipulator unit allows relative motion of a datum point with respect to end effector unit. The relative motion of a platform and a material deposition head in a plane (X- and Y- axis) allows deposition along a planar layer and then process increments to the next layer (Z-).

Various system architectures have been used for the same intent. This includes:

- Cartesian architecture
- Delta architecture
- Open-Loop articulated Robot
- Scara- architecture

1.1 Cartesian architecture

Cartesian architecture (Figure 1) is one of the most popular architectures in 3D printing [7]. It comprises of three orthogonal linear drives. Inherent to the Cartesian architecture is the ease of implementation.

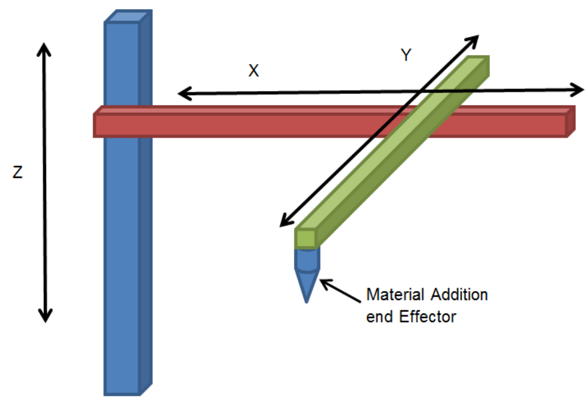


Figure 1. Cartesian Architecture for 3D printing

The orthogonal linear drives, work in conjunction so that the spatial location of the material deposition head is described as:

$P(t) = \{ \alpha x(t), \beta y(t), \Omega z(t) \}$ …………………..Eq (1)

Where α,β,Ω are the mechanical Drive constants that translate the CAD model space to equivalent printer space. Inherent to the Cartesian system is ease of manipulation hence the implementation. The expansion be cascading of such as system, sustains the total degrees of freedom to 3.

1.2 Delta architecture

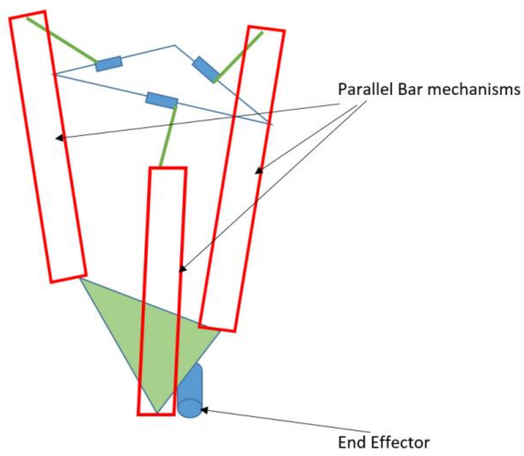


Figure 2: Delta Architecture

The Delta architecture (Figure 2) is based on attaching the material addition end effector onto a platform that is tied to the machine base using three parallel bar mechanisms. This unique mechanism allows sustenance of the orientation of the end effector while allowing the relative motion with respect to the substrate. While many commercial pick and place machines are based on the delta architecture, usage of the same for 3D printing is yet in its infancy. Attempts have been made amongst the hobby community to build systems based on RepRap Framework [16]. A delta system is complex, and expansion of work envelope by cascading would make the spatial manipulation very complex. While degrees of freedom for individual delta system is 3; with cascaded Delta system, the degrees of freedom changes to multiples of the number of units. For example, cascading two delta system enhances the degrees of freedom to 6.

1.3 Open loop articulated Robot

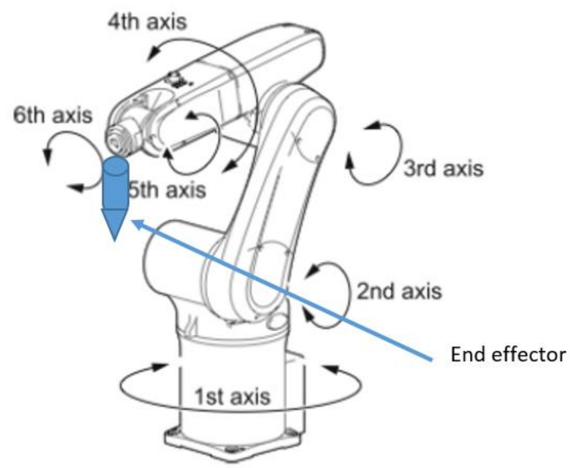


Figure 3: Open loop articulated Robot system

Systems such as MultiFab at Research center for Advanced Manufacturing [8,9] are based on articulated Robot Architecture. Similarly viridis3d [10] is employing articulated robots to 3D print molds and other metal and ceramic structures. The ability to articulate the material deposition enhances the ability of the system by allowing material addition along multiple directions. The open loop configuration (Figure 3) and higher degree of articulability of the material addition end effector allow accessing the datum from many different angles. When cascaded, the flexibility offered by such a system one hand has cost attribute, on the other renders many axes redundant.

1.4 Scara Architecture

As described in the Figure 4, the Scara arm comprises of two link arm that compliant in one plane(X-Y) but rigid along the normal direction (Z). The end effector is attached to the end of two link arm and Manipulation of the two links in the arm allows material deposition along the horizontal plane. Once a layer is deposited the arm may increment along the z direction.

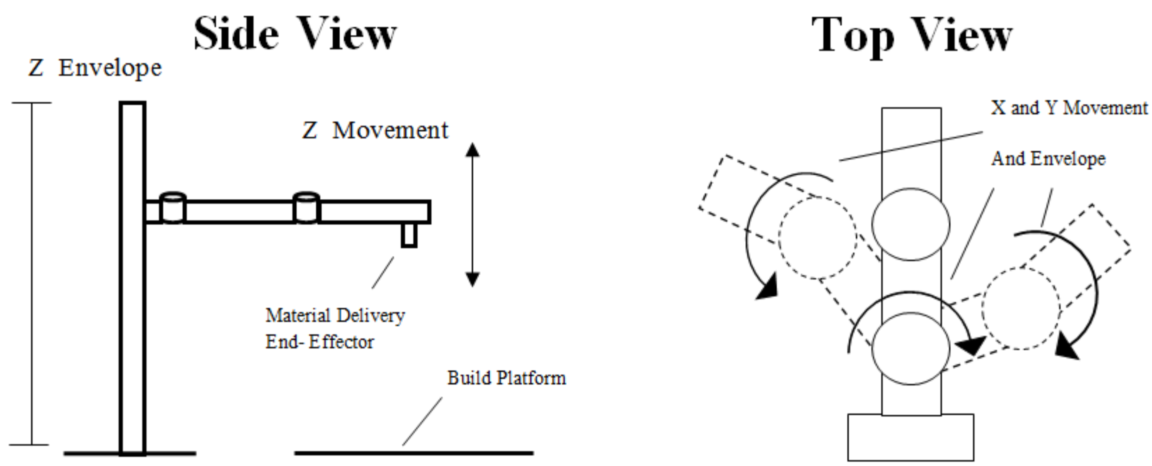


Figure 4. Scara Architecture system

Okabe et al [11] describe a framework for SCARA based 3D printing method. A RepRap project for the same is described by Nicholas. Seward[12]. Similar to the articulated arm, a reconfigurable system based on Scara architecture will render many axes redundant. Another disadvantage would be increase in the beam length hence loss in part accuracy.

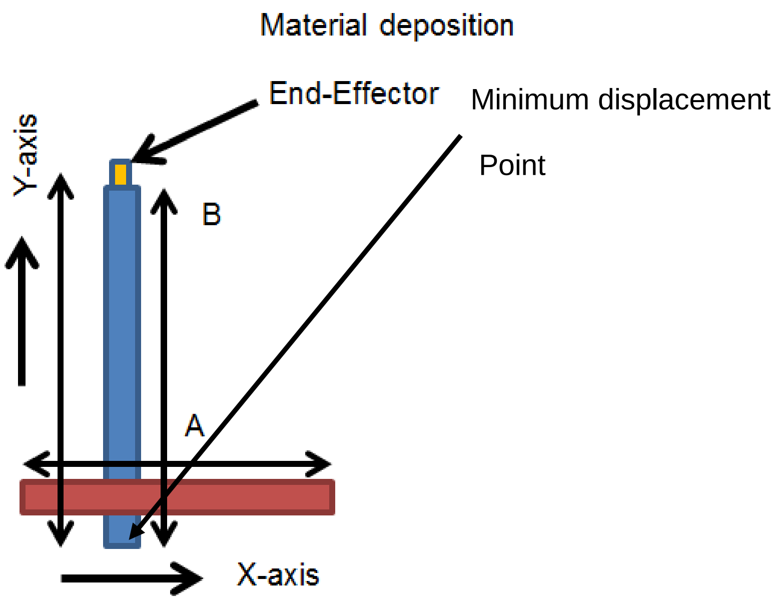
2.0 Reconfigurable system Design

Motivated by the ease of implementation of the Cartesian architecture and the ability to scale not only the system mechanical hardware but also the framework, following two approaches were explored:

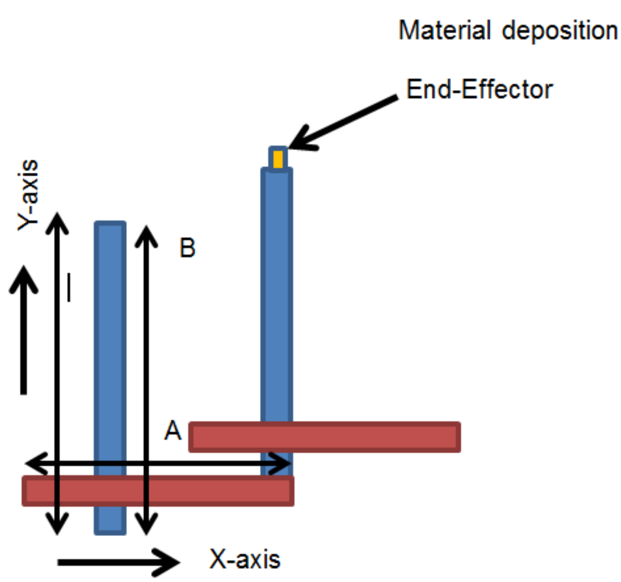
- Axis stacking
- Common vehicle

2.1 Axis Stacking

Stacked Axes, reconfigurable system proposed by us is based on following a homogeneous basis; that is, a common mechanism is reorganized in a linear fashion. The system borrows from the ease of implementation of Cartesian-Architecture. This approach as shown in the Figure 5, is based on attaching single Cartesian axes set in a cascaded manner such that the minimum displacement point of a X-Y manipulator is attached at the location of the end effector displacement point of previous set. The end effector is attached to the terminal point of the last axes set.



(a) Single Axes set



(b) Stacked multiple axes set

Figure 5: Reconfigurable Cartesian system

While the mapping of the Computer model space to a basic Cartesian system may ensue in linear translation of the spatial location and movements into equivalent drive displacement; the same may not apply for the cascaded system. In order to retain the respective independence of the drives, the mapping of the computer model space to the machine coordinates is expressed as:

$$\text{For} \begin{cases} 0 \le x(t) < A \\ 0 \le y(t) < B \\ 0 \le z(t) < C \end{cases} \qquad P(t) = \{ \alpha x(t), \beta y(t), \Omega z(t) \} \ \ldots\ldots\ldots\ldots \text{Eq(2)}$$

Where A, B, and C are the maximum displacement along the axes X, Y and Z respectively. α,β,Ω are the corresponding linear multiples to translate the cad model space into the additive manufacturing drive space.

For a two Cartesian based system, corresponding equation will be modified to

$$\text{For} \begin{cases} x(t) > A \\ y(t) > B \\ z(t) > C \end{cases} \qquad P(t) = \{ \alpha(x(t)-A), \beta(y(t)-B), \Omega(z(t)-C) \} \ \ldots\ldots\ldots\ldots \text{Eq(3)}$$

It is assumed that α,β,Ω are same for the additional axes.

For a multiple Cartesian based system, corresponding equation will be modified to

$$\text{For} \begin{cases} x(t) > (i-1) * A \\ y(t) > (i-1) * B \\ z(t) > (i-1) * C \end{cases} \qquad P(t) = \{ \alpha(x(t)-(i-1)*A), \beta(y(t)-(i-1)*B), \Omega(z(t)-(i-1)*C) \}$$

For $1 \le i \le n$ ………… Eq(4)

It is assumed that α,β,Ω are same for the additional axes.

It may be noted that the current configuration is replicated for the X-Y planes. Theoretically, the inclusion of Z- coordinate may be done to enhance the spatial volume; however, practical issues such as increase in the effective beam length of the axes ensue. To counter the same, additional implements such as support structures for the overhanging X and Y drives may be use. One such implement under consideration is uniform stiffness roll up extendible spring. Such implements have find successful usage in mail stacking trays for postal automation machines and popular garage door mechanism. The support structure features may limit the free movement of the end effector; therefore, addition of the Z-axis may be done on need basis. Identification of a custom spring design and manufacturer is still being pursued by the researchers and the same would be reported in future work by research team. For a sturdy and easy to scale systems, the framework proposed, can include the Z-axis seamlessly. We explored few options for the functionality with limited success. The same are described in later sections. An extensive implementation and testing would be a future work.

2.2 Common Vehicle

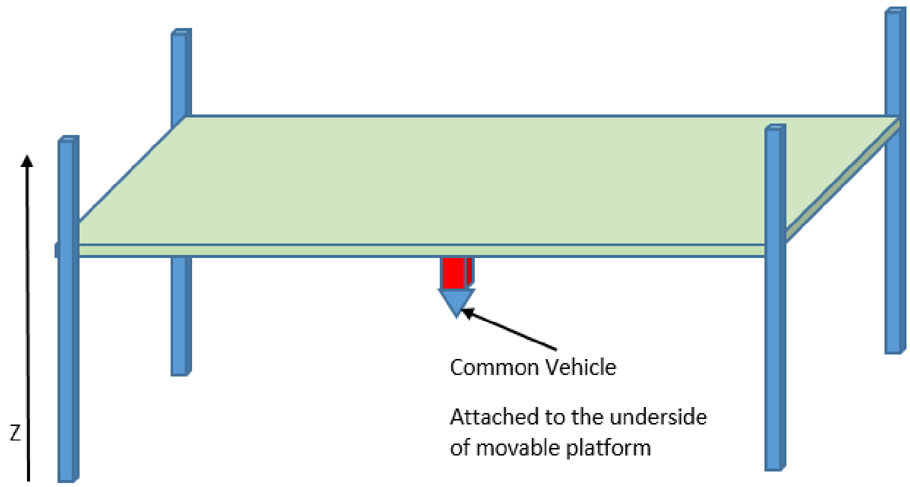
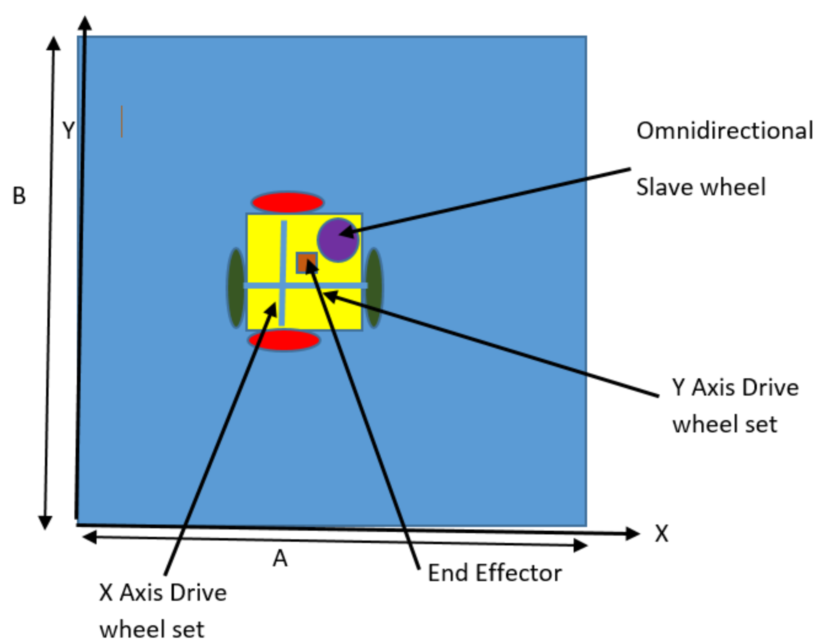
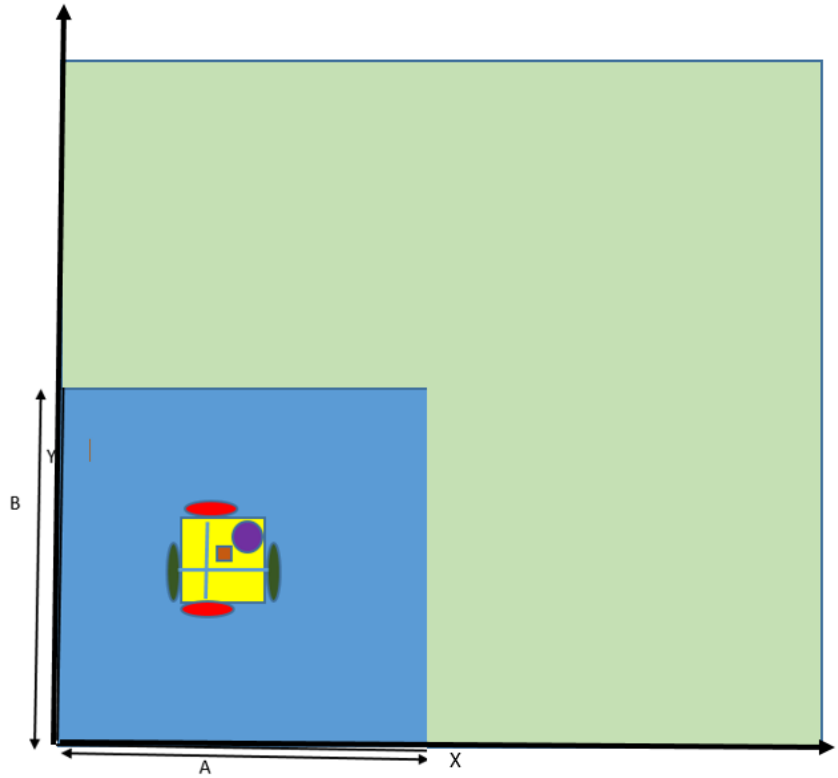


Figure 6: common Vehicle Overall system description



(a) Unit work Plane



(b) Enhanced Work Plane

Figure 7. Common Vehicle Approach

Inherent to most of the drives used for spatial manipulation of end effector is the rotary to linear motion conversion. The common vehicle approach eliminates the need for a complex drive. As described in Figure 6, the spatial manipulation is done by movement of a vehicle along the underside of a table.

The vehicle system is based on two orthogonally placed wheel sets (Figure 7 (a)) to traverse in either directions. A slave omnidirectional wheel serves as the third support. Depending on the required direction of motion (X- or Y-) the wheel set is actuated. Contrary to the Cartesian system, where both the axes may be actuated simultaneously, common vehicle has the wheel set for single direction actuated at any given instance.

In order to enlarge the work envelope the supporting platforms are added. As described in the Figure 7(b), the vehicle is unaltered, the platform for the vehicle traversal is enlarged as needed. The mapping of the computer model space to drive space has the same basis as the cascaded Cartesian arrangement. However, the Common vehicle system may be replicated along two Primary axes (X-,Y-). Third Axis (Z-) would need an exclusive linear drive to elevate the plane of the vehicle displacement.

3 Test setup

3.1 Cascaded Cartesian arrangement

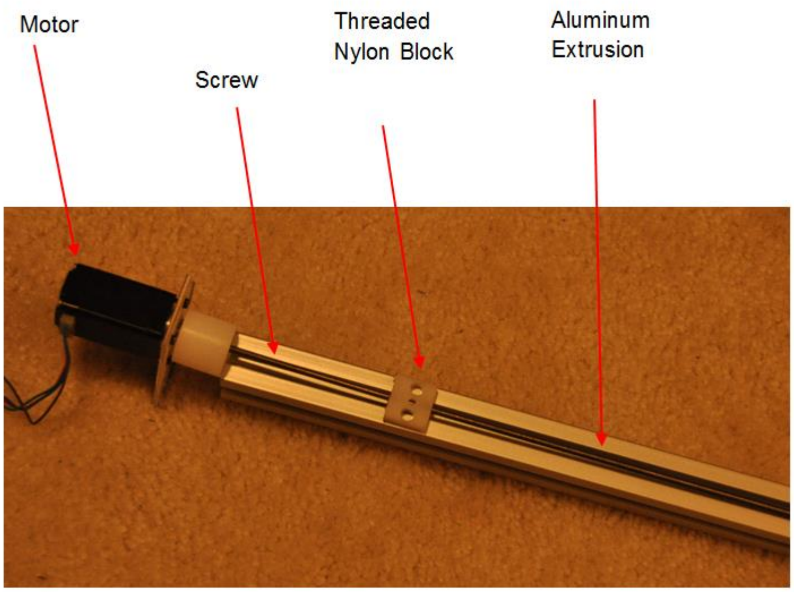
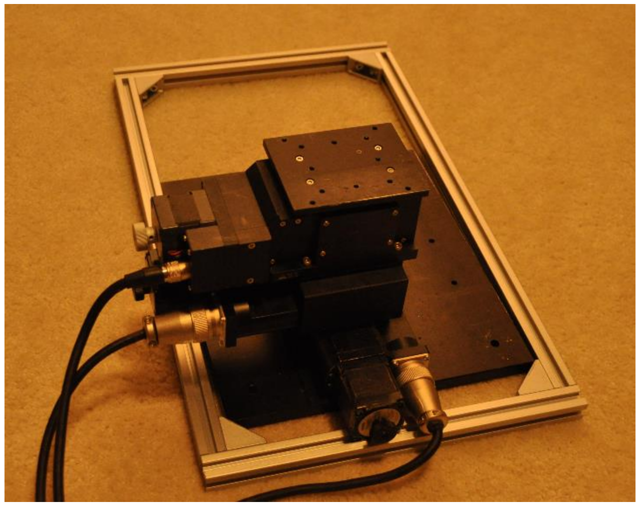
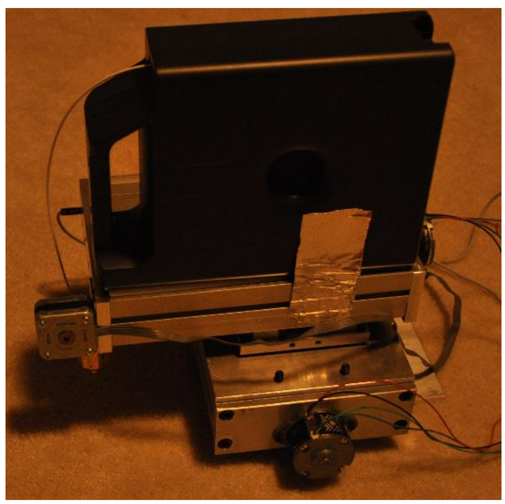


Figure 8: Proposed simple linear drive based on Aluminum Extrusion

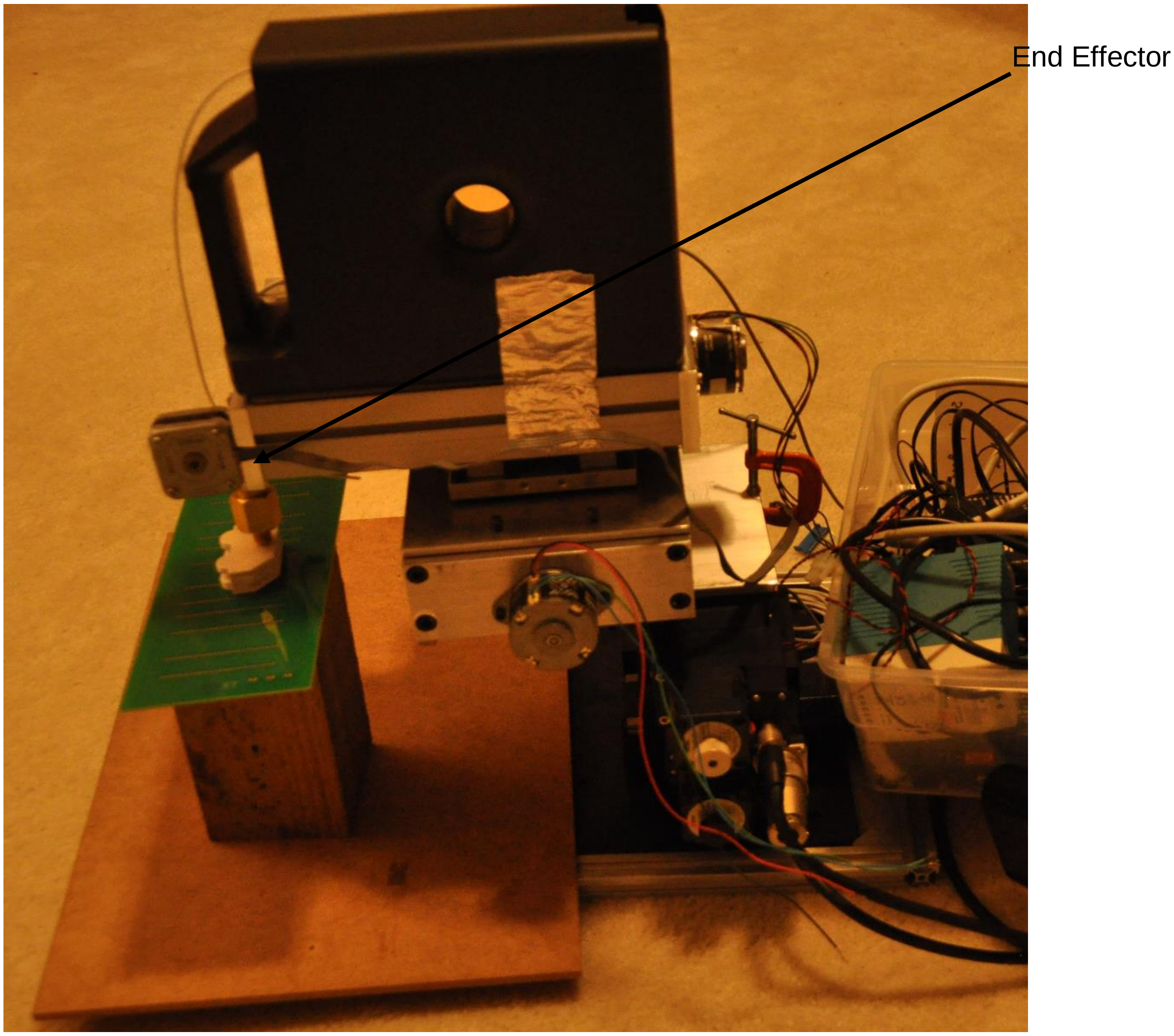
Per the initial plan, fundamental linear drive of the Cartesian system as described in the Figure 8 would comprises of aluminum Extrusions. The slots in the extrusion serve as guide for a nylon block. The nylon block has compatible features to slide in the aluminum guide. The block is threaded and a matching threaded axle engages with the nylon block. The nylon block supports an attachment platform. The threaded axle engages with a stepper motor. The rotational motion of the stepper motor translates into linear motion of the nut. The nut is slotted along the threaded hole to reduce the backlash. Each drive has a touch sensor at the end of the drive to register starting position. The linear motion would be implemented using open loop control. The system is compact, extremely cheap; however, accurate. Owing to the aspect ratio and unavailability of suitable interfaces and machining resources, the experimental setup was modified.



(a) 3- axis drive,(First Cartesian)



(b) 2- axis drive with end effector(Second Cartesian)



(c) Combined Cascaded Cartesian drive

Figure 9: Experimental Setup for Cascaded Cartesian manipulator

Figure 9 describes the experimental setup. The setup is based on a 3-axis X-,Y-Z- stage (First Cartesian) salvaged from a semiconductor assembly robot. The system offers a positional feedback. Additional setup (Second Cartesian) was prepared with the help of a two axis linear drive based on aluminum extrusion. The Extrusion system was attached at the end effector point (Figure 5) of the two axis drive. Similarly the two axis drive is connected to the 3-axis stage along its end effector point Only contributing drive in the Z-direction is the Z-drive of the 3 axis stage therefore the displacement in the z-direction is very limited. The X-,Y- displacement is cumulative of the two drives.

The overall weight of the 3-axis drive is significant and it is structurally very robust therefore the deviations due to axes deformation are none. The material deposition end effector is attached to the terminal drive.

3.2 Common vehicle arrangement

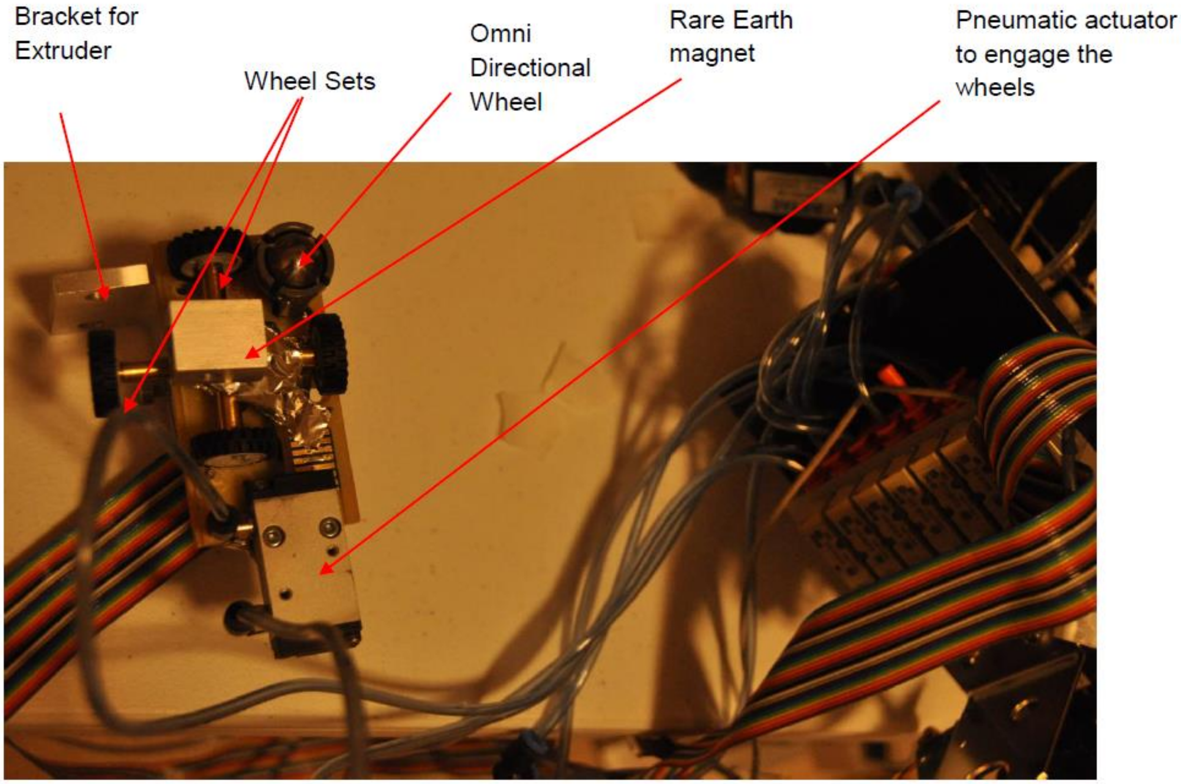


Figure 10: Common Vehicle Experimental Setup

The common vehicle arrangement is based on attaching a vehicle in inverted configuration as described in the Figure 10 and Figure 11. The platform for displacement is made from a ferrous material. A rare earth magnet is attached to the vehicle platform and is placed at fixed distance from the ferrous material platform. Two sets of three wheels are placed with the axes directions fixed in orthogonal directions. The wheels are driven by two stepper motors. A third omnidirectional wheel establishes a triangular point of support for the vehicle to move. In order to engage and disengage with the ferrous surface; the two set of wheels are actuated with the help of a pancake pneumatic cylinder. Depending upon the desired direction of displacement, one wheel set is lowered whereas the other wheel set is lifted.

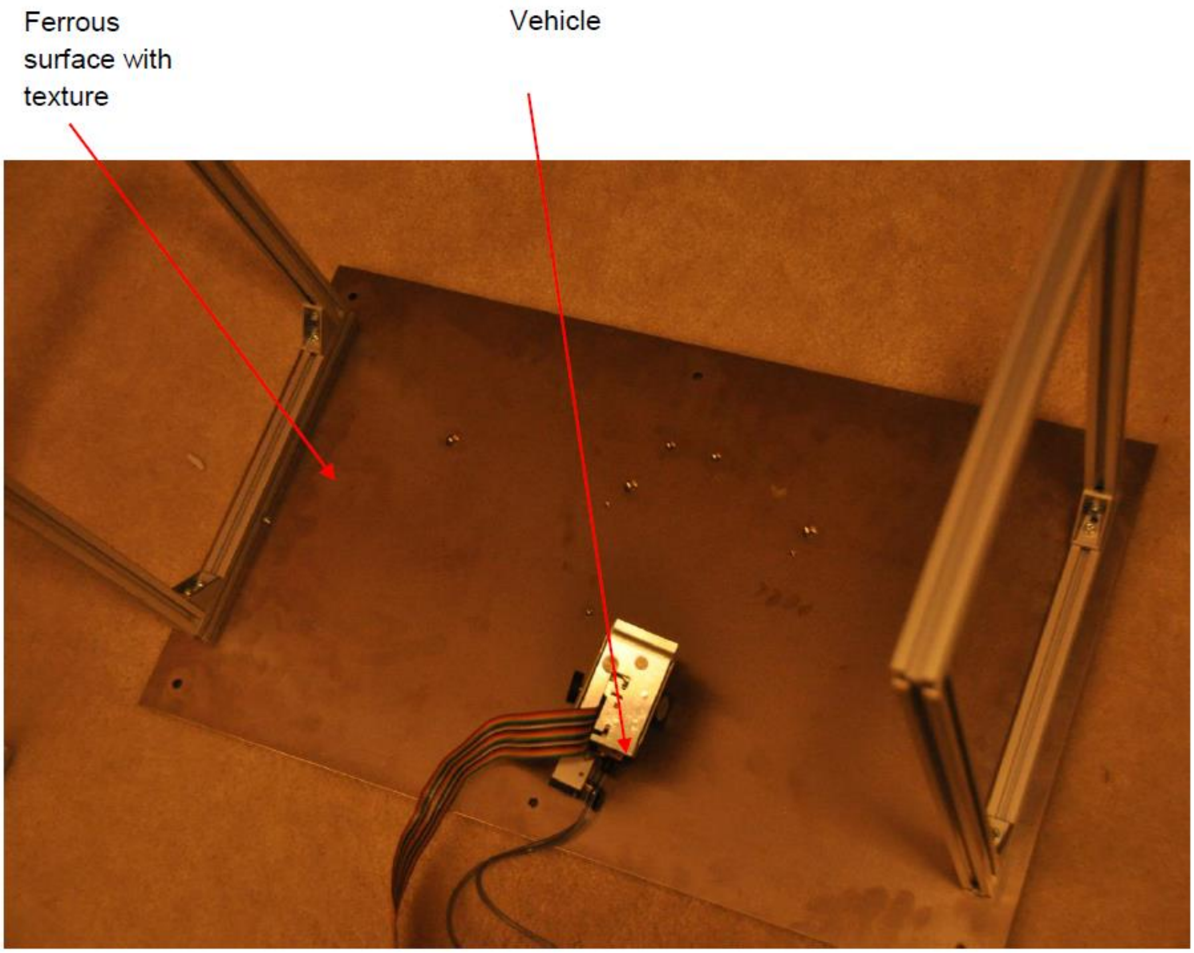


Figure 11: Underside of the common vehicle arrangement based system

The ferrous material surface has anisotropic guiding features to sustain the direction of the wheels. Additionally, the wheel contact is near knife edge shaped so that once engaged with the surface it sustains the direction of motion. The material deposition head is attached to the vehicle.

A RepRap based architecture is used for controlling the drives. The drive is controlled by Arduino Mega. Arduino is one of the most popular microcontroller boards within the hobby community especially the RepRap. Arduino mega offers more GPIO pins for controlling and driving the system.

Results and future work:

Implementation of the Z-axis control for the Cascaded Cartesian arrangement was done successfully. Figure 12 describes a part manufactured by the Cartesian axis stacking approach. While for most part the deposition is uniform, along the interfaces where we make transition from one Cartesian system to another, there is a noticeable interface.

Following from Equation 4, for a multiple Cartesian based system, corresponding translation of the CAD space to the linear drive space would be

$$\text{For} \begin{cases} x(t) > (i-1) * A \\ y(t) > (i-1) * B \\ z(t) > (i-1) * C \end{cases}$$

$P(t) = \{ \alpha(x(t)-(i-1)*A+(i-1)*ErrX_i), \beta(y(t)- (i-1)*B +(i-1)*ErrY_i), \Omega(z(t)- (i-1)*C)+ (i-1)*ErrZ_i \}$

For $1 \leq i \leq n$ .... Eq(5)

Where $ErrX_i$, $ErrY_i$, Err_iZ are the errors arising at i[th] transition interface.

For the System under consideration, the bead size of deposited material is 0.32mm and corresponding deformation of the transition zone is observed to be within 0.15mm to 0.2mm. Slowing of drive due to computational time when transitioning from one region to another as well as the dimensional tolerances may be attributed to this observation

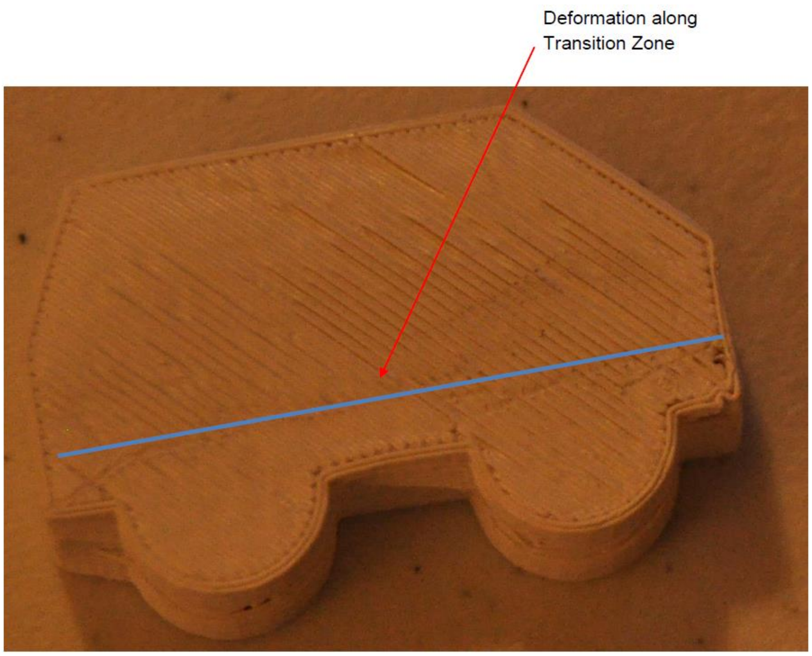


Figure 12 Part printed by Cascaded Cartesian experimental setup

The system based on the Common vehicle approach couldn't be completed to the extent of part manufacturing. The system is very sensitive to the loads attached. Also significant acceleration and deceleration cause the vehicle to Drift.

The system and, experimental results suggest that a reconfigurable system for 3D printing is conceivable and may be implemented for significantly lesser cost. Issues such as possible deflection need to address. Quantitate evaluation, aluminum extrusion based system and the completion of common vehicle based architecture would be the immediate endeavor.

Acknowledgements

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