Design and Evaluation of a Novel Laser-Cutting Machine for Computer-Aided Manufacturing of Laminated Engineering Materials

Sangeun Choi[1], and Wyatt S. Newman[2]

Abstract

This paper presents the recent redesign of a tangent-cutting machine for CAM-LEM (Computer-Aided Manufacturing of Laminated Engineering Materials). Our former 5-axis, serial-joint, open-chain mechanism for laser cutting has been reduced to two parallel, 2-axis kinematic chains and articulated optics. The redesign results in lower inertias, higher stiffnesses, and less calibration sensitivity to homing and misalignment of axes. As a result, the system has higher acceleration capability, higher tracking bandwidth (translating into faster laser cutting) and greater precision, enabling improved build rates. The new design is presented, along with experimental evaluation of the performance improvements. Performance improvements are quantified in terms of calibration sensitivity, tracking bandwidth, and resonant frequencies.

1. Introduction

Computer-Aided Manufacturing of Laminated Engineering Materials (CAM-LEM), being pursued at Case Western Reserve University, is an approach to Solid Freeform Fabrication (SFF) that offers the potential for fast build rates and flexibility in material selection [1], [2], [3]. While a wide variety of both commercial and experimental SFF approaches exists, most are additive techniques. Notably, Stereolithography [6], Selective Laser Sintering [7], Fused Deposition Modeling [8], and 3-D Printing [9] are well-known approaches for building up 3-D solids through incremental deposition, solidification, or fusing of material for layer-by-layer growth in the vertical direction. In contrast, Laminated Object Manufacturing [10], ShapeMaker [11] and CAM-LEM use sheet-based feedstock, and objects are built up by cutting and stacking (or stacking then cutting) successive layers. This latter approach has the potential for much faster build rates, particularly for large objects, since material removal about a perimeter can be significantly faster than material deposition throughout the enclosed area.

Another distinguishing feature of CAM-LEM is exploitation of a model's surface-normal information. By forming tapered edges on each layer (i.e., tangent cutting), thicker build layers can be used without compromising surface finish (see, e.g., [4], [5], [12]). Shape Deposition Modelling [13], ShapeMaker, Stratoconception [14] and CAM-LEM are unusual among SFF methods in exploiting tangent cutting.

Our 5-axis "alpha" CAM-LEM machine design has been described in [2], [3]. This design was successful in laser cutting thick sheet materials to produce ruled-surface edges. In the current presentation, we describe redesign of the CAM-LEM system to achieve lower cost, better precision and faster cutting. We first present a review of the 5-axis "alpha" design, then compare it to our new "beta" design—a simpler, cheaper 4-axis system. We present analysis showing

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[1] graduate student, Dept of Mechanical Engineering, Case Western Reserve University

[2] Professor, Dept of Electrical Engineering and Computer Science, Case Western Reserve University

that the precision of the 4-axis design is less sensitive to parametric uncertainties than the 5-axis design. Subsequently, we present the measured dynamic properties of both the alpha and beta machines, including consideration of mechanical resonances. It is shown that the new system is capable of higher-speed laser cutting than the former design.

2. Review of CAM-LEM 5-Axis Alpha Design

Our 5-axis system, shown in Fig 1, consists of 3 translational axes (x,y,z) and two rotational axes (roll and pitch) that position and orient a 6"x 6" cutting table beneath a stationary laser source. Sheet material is clamped to the cutting table with vacuum pressure exerted though aluminum honeycomb cells. The cutting table is mounted with an offset 77.5 mm above the intersection of the two rotary axes to maximize clearance with the laser. To achieve the required positions and orientations for cutting the desired tangents about the boundary of a part slice, motion of the x and y axes must be coordinated with the roll and pitch angles of the cutting table. Vertical (z-axis) motion is incorporated in order to keep the material at the laser focal point, at which air ejected from a nozzle helps remove debris and assist cutting. The maximum orientation angle of the cutting table surface is constrained by the clearance of the laser nozzle such that the pitch and roll axes are limited to ± 73 degrees of motion from vertical during cutting.

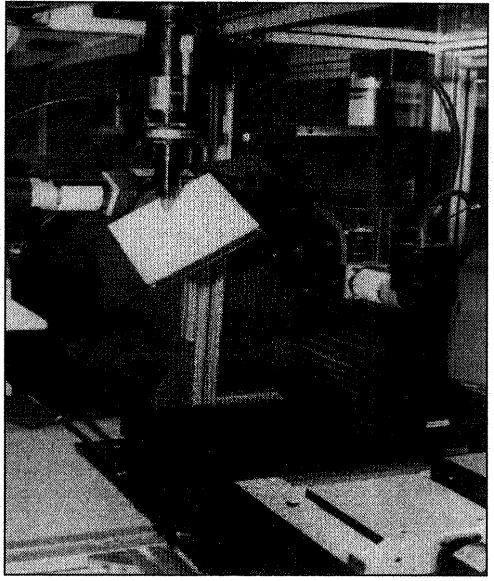


Fig1: The 5-axis cutting machine

Kinematics of the alpha design are shown schematically in Fig 2. This design has all five axes connected serially. While this construction has achieved the desired kinematic range of motions, it includes some undesirable dynamic and calibration problems. The relatively tall z axis must carry both the roll and pitch axes, which rotate the cutting table under the stationary laser beam. The z translation is necessary to keep the cutting point at the laser focus when the cutting table is tilted. However, the pitch and roll axes are relatively heavy, resulting in problematic z-axis vibration modes. Further, the weight of the pitch and roll axes carried by the x, y and z axes results in a gravity pre-load that increases the Coulomb friction and the inertia seen by the translational axes, resulting in reduced trajectory-tracking performance. In addition to the dynamic features, by stacking all axes serially, relatively small calibration errors (e.g., misalignment of the roll axis with respect to the x axis and non-orthogonality and non-intersection of the roll and pitch axes) are amplified in terms of laser-cutting distortions, particularly at extreme tangent angles.

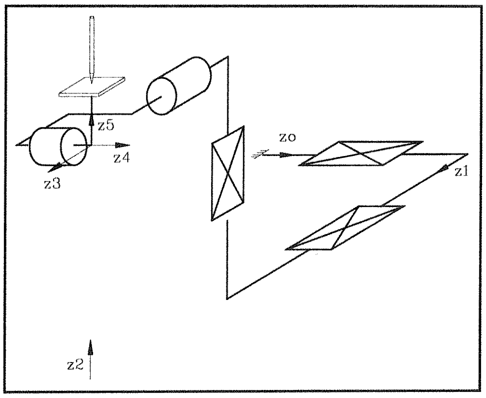


Fig 2: Five axis system architecture

3. The CAM-LEM 4-Axis Beta Design

Fig. 3 shows a schematic description of the 4-axis beta design. In this design, the four controlled axes are configured as two, 2-DOF kinematic chains with separate paths to ground. To accomplish this, an x-y cutting platform is used in combination with an articulated laser head. The laser head rotates about a fixed center of rotation–the focal point of the laser–via two orthogonal rotation axes lying in the cutting plane. With this design variation, multiple benefits accrue. First, the required number of servoed degrees of freedom is reduced from 5 to 4, reducing complexity and still achieving the required mobility. Second, the pitch and roll axes do not have to be supported by x, y and z axes, reducing the gravity force and moment loading on these axes. Third, the decoupled system has lower x-y table inertia, enabling more nimble contour following during laser cutting. Fourth, by providing parallel paths to ground for the x-y table and for the pitch-roll axes, the system can be much stiffer and have less resonance problems. Fifth, by separating the x-y vs. pitch-roll degrees of freedom, the system is easier to calibrate. Finally, since the beta design does not require tilting the cutting platform, the cutting table is easier to design and the clamping requirement on the sheet material being cut is less demanding.

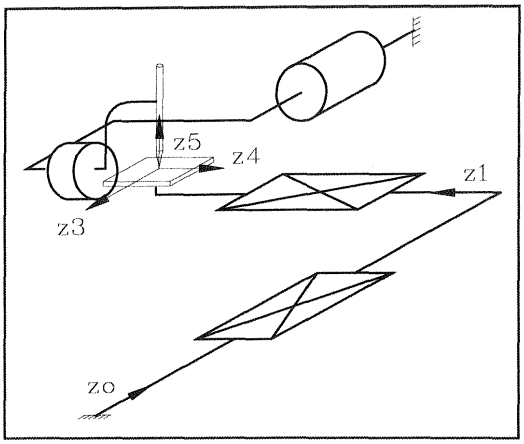


Fig 3: Four axis system architecture

Fig 4 shows the structure of the new 4-axis cutting platform. The x-y cutting table controls the perimeter of the contour to be laser cut, and the pitch and roll axes control the tangent angle of the edge, independent of the x-y motion. Control of the angle of approach of the laser beam requires use of moving optics. As can be seen from Fig 4, the beam delivery system includes six 90-deg elbow bends. At each elbow, there is an internal mirror mounted at 45 degrees. At two of these bends, there is a rotational degree of freedom (a commercial component from Laser Mechanisms, Inc.). This construction is a variant on 6-dof (degree-of-freedom) and 7-dof passive beam delivery systems used in laser surgery. It permits maintenance of good optical alignment while providing for redirection of the laser-beam. In our laser-cutting design, we require only two degrees of freedom of the articulated optics—provided these degrees of freedom are aligned as shown in Figs 3 and 4.

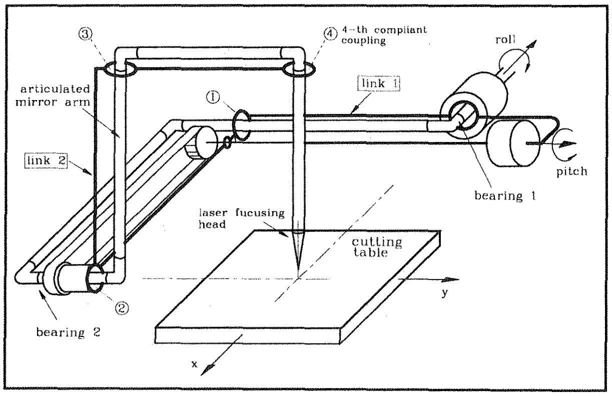


Fig 4: Structure of 4-axis cutting platform

The resulting beam-delivery system is capable of rotating the direction of approach of the laser beam about a fixed point in space, which is designed to coincide with the laser focal point at the surface of the x-y cutting table. Actuation of the passive laser mechanism is performed by two rotational motors. If the axes of these motors are not precisely aligned with the axes of the beam-delivery elbow bearings, large binding moments will be exerted on the elbows, resulting in beam misalignment and possible damage to the precision bearings of the articulated optics. To accommodate inevitable small misalignments, the passive beam-delivery mechanism is driven via compliant couplings to the drive mechanism. The drive mechanism is a 2-dof serial-link, open kinematic chain (a 2-dof robot). Four compliant couplings are used, as labeled in Fig 4.

The roll axis of the drive mechanism drives a yoke, which rotates the entire beam-delivery mechanism as well as the pitch motor. The pitch motor actuates the second degree of freedom, moving only the beam-delivery components past the second articulated mirror. To reduce the inertia and gravity load seen by the roll actuator, the pitch motor is located near the roll motor, offset from the roll axis to act as a counterbalance. The pitch motor drives the second degree of freedom via a shaft extension to a pulley and toothed belt.

The fully-assembled beta machine is shown in Fig 5. The 6"x6" cutting table is cantilevered from a vertical support mounted on the x-y sled. This support structure permits the roll axis to swing the yoke below the cutting table, extending the range of accessible angles. The reachable range of roll and pitch angles is at least +/- 80 deg over the full 6"x6" cutting table range of motion.

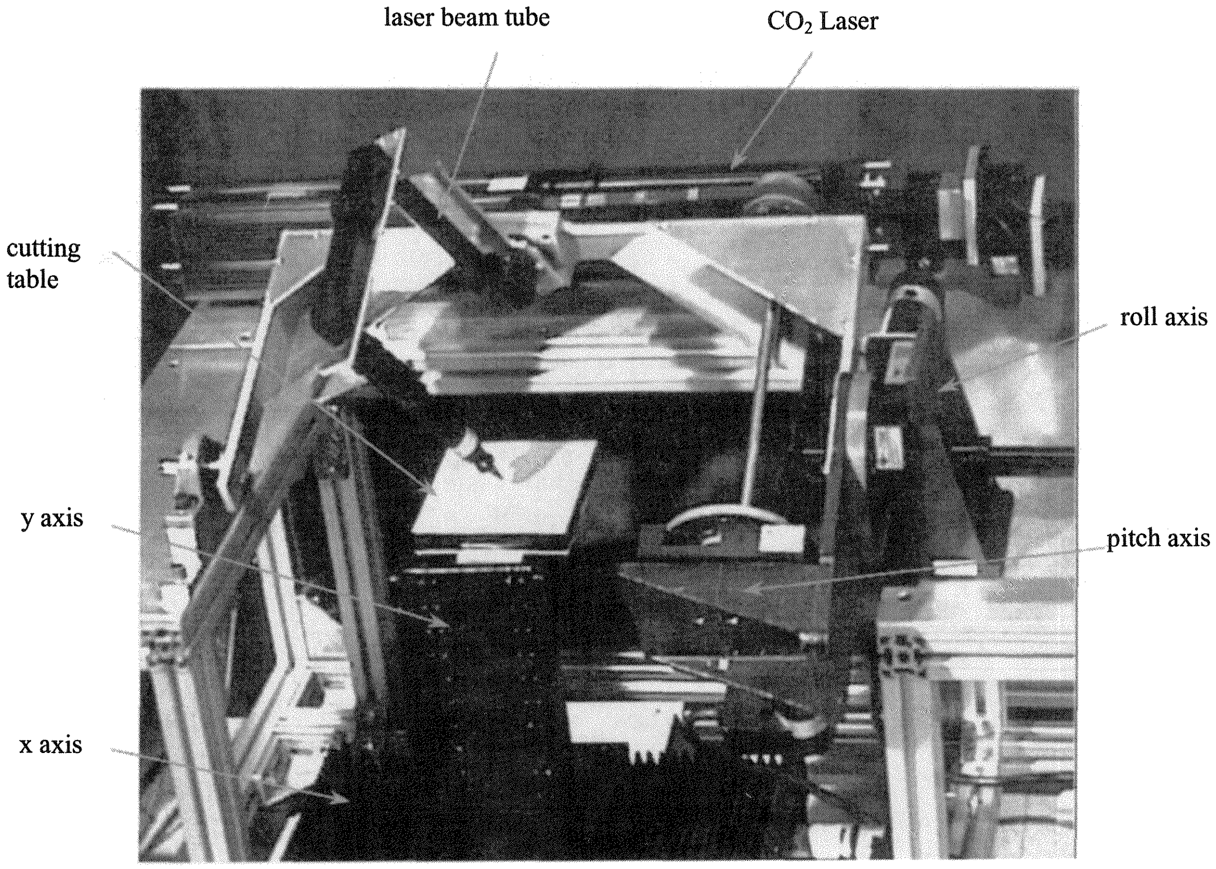


Fig 5: The new 4-axis cutting platform

4. Analysis of Alpha and Beta Machine Calibration Sensitivities

One of the advantages of the new 4-axis design is reduced sensitivity to calibration errors. To evaluate this claim, a sensitivity analysis was performed, as described by Fig 6.

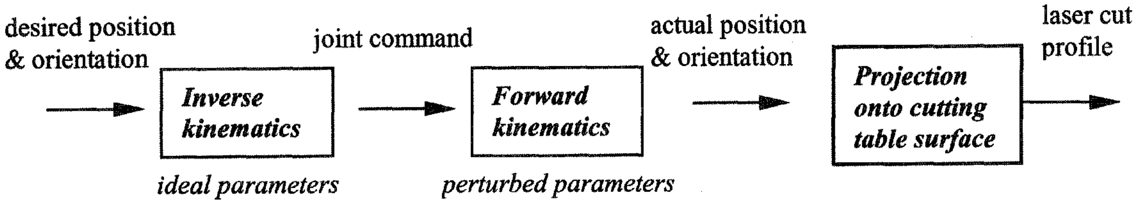
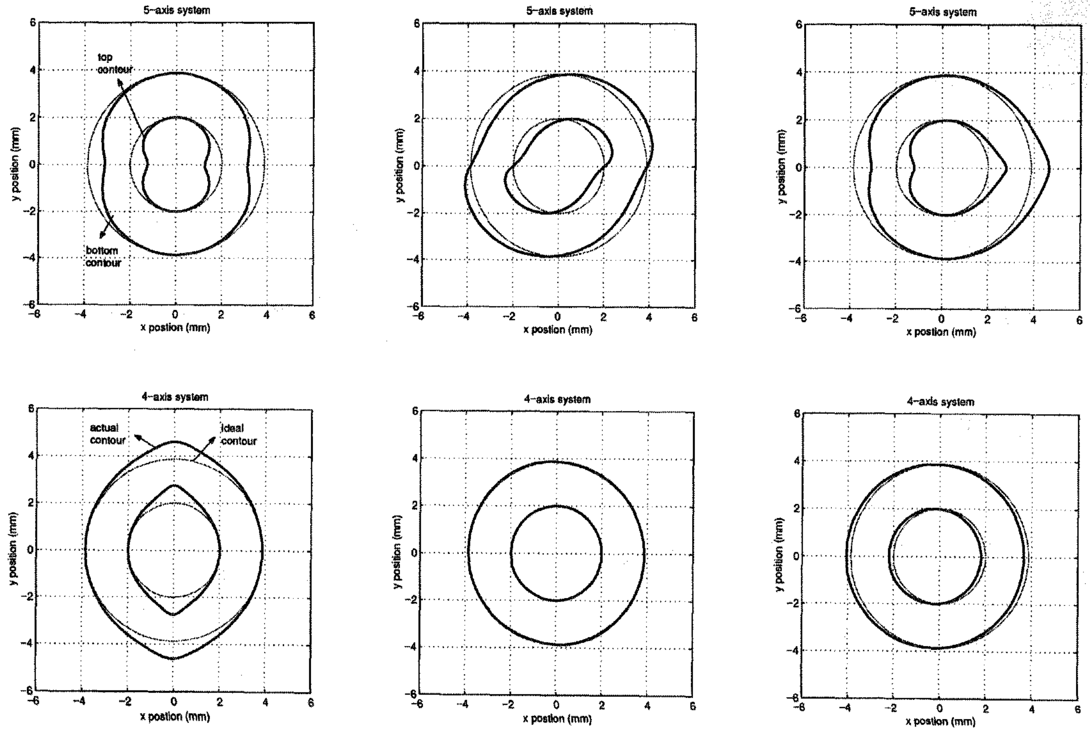


Fig 6: Scheme for the sensitivity analysis

To illustrate this analysis, we consider cutting a simple shape—a frustum of a cone with a 4 mm top (minor) diameter and a 7.73 mm bottom (major) diameter cut from a 0.5 mm thick sheet, constituting a tangent angle of 75 deg. For the beta design, the inverse kinematics corresponding to the desired cut shape prescribes sinusoidal x and y displacements, phase shifted by 90 deg, and sinusoidal roll and pitch displacements, also phase shifted by 90 deg. In the case of the alpha design, if the frustum is to be cut at the center of the cutting table, then sinusoidal x, y, roll and pitch angles are also required, while the z-axis is at a constant elevation.



(a)
pitch/roll axes offset by 0.2 mm

(b)
pitch/roll axes skewed by 0.5 deg from orthogonal

(c)
x-axis home position shifted by 0.2 mm

Fig 7: Contour cut shapes due to calibration errors

We illustrate three relatively strong influences on cut accuracy vs. alignment errors. The first is an offset between the (ideally intersecting) pitch and roll axes. The second is non-orthogonal pitch and roll axes, and the third is an error in the home position of the x axis. Fig 7 shows the results of the analysis per Fig 6. In Fig. 7a, the pitch and roll axes are offset by 0.2 mm. In Fig 7b, the pitch and roll axes are skewed by 0.5 deg from perpendicular. In Fig 7c, the x-axis home position is shifted by 0.2 mm.

For case 7a, an offset between the pitch and roll axes, the alpha and beta machines produce comparable magnitudes of distortion. However, for cases b and c, the alpha design shows significant distortions while the beta design is virtually immune to these types of errors. The distortion in Fig. 7b, due to non-orthogonal axes, is negligible for the beta machine. Further, for the beta design an x-home error results in a pure shift; there is no distortion of the cut shape. We thus see that the beta design has low sensitivity to kinematic imprecisions. We further see, however, that it is important to align the roll and pitch axes to be (ideally) coplanar (intersecting). In the beta machine design, this was done by assembling all parts using a precision jig designed for this purpose.

5. Analysis of Alpha and Beta Machine Dynamics

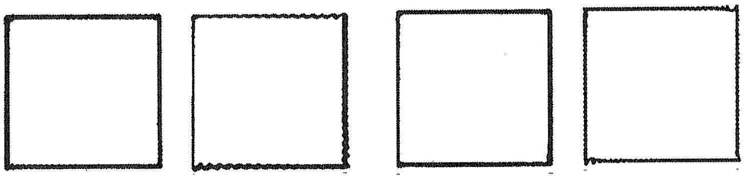
In addition to improved calibration precision, we had further proposed that the new design would be capable of faster laser cutting. To validate this proposition, we performed two sets of characterization: identification of dynamic parameters, and evaluation of influence of mechanical resonances on laser cutting. The dynamic parameters evaluated included: Coulomb friction, gravity loading, viscous friction, maximum velocity, maximum acceleration, and inertia. These terms were identified by tuning feedforward control efforts and analyzing net feedforward and feedback control terms resulting from tracking trial trajectories. Using low-speed sinusoidal trajectories, Coulomb friction and gravity terms dominated the required control efforts. Having identified the Coulomb and gravity terms, the frequency of the test sinusoidal motion was increased, introducing significant viscous friction effects in the net control effort. At still higher frequencies, inertial terms dominate. (The amplitude of the sinusoids had to be decreased at higher frequencies to avoid nonlinear distortions due to velocity saturation and force/torque saturation.) Finally, trapezoidal velocity profile trajectories were commanded for each joint, and the commanded maximum velocity and maximum acceleration were increased incrementally until saturation effects were observed.

The beta design did exhibit improved dynamic properties for the x and y axes. Coulomb and viscous friction are lower, inertias are lower, and maximum accelerations are higher. These benefits are relatively modest, however, since the lead-screw pitches constitute relatively large gear reductions, and thus the reflected inertias of the motors dominate the dynamic loads. As a result, the net improvement in acceleration of the slowest translational axis is only about 26 %. A stronger advantage of the 4-axis design is that there is no third translational axis, and thus the dynamic limitations of the z-axis do not restrict the beta design performance.

A drawback of the beta design is that orientation (pitch and roll) acceleration is slower than that of the alpha design, at 67 % of the original worst-case available angular acceleration. This reduced response is due to the inertia of the yoke in the beta design used to drive the articulated optics. Thus, the beta design is somewhat faster in position control, but slower in orientation control. The resulting speed comparison for coordinated laser cutting depends on the shape of the part to be cut; outlines with high spatial frequencies and relatively low tangent curvatures could be cut more rapidly with the beta design, whereas part shapes with rapid tangent variations would be cut more slowly by the beta design.

A more dramatic improvement in dynamic performance is due to the stiffer structure and correspondingly higher resonant frequencies of the beta design. Notably, the serial-link structure of the alpha design resulted in a lowest translational resonant frequency of 22 Hz. With the new design, this frequency increased to 65 Hz. Within the velocity and acceleration saturation constraints, this higher resonant frequency corresponds to a higher tracking bandwidth. The higher resonance theoretically enables cutting speeds 3 times higher. However, incorporating consideration the nonlinear effects of acceleration and velocity saturation reduces the magnitude of potential cutting-speed improvement.

To illustrate the effects of mechanical resonances on laser cutting, including consideration of acceleration saturation, we performed a simple test of cutting squares from poster board on both the alpha and beta machines. The results are shown in Fig.8. The trajectory specified for these test patterns was not dynamically feasible, since the cutting speed was held constant. As a result, the corners of the desired square trajectories corresponded to infinite accelerations in the x and y directions. In attempting to follow these untrackable trajectories, the alpha and beta designs exerted maximum accelerations and induced excitations of resonances. The influence of such ringing is apparent in the spatial oscillations of the laser-cut edges.



6 mm/sec *10 mm/sec* *10 mm/sec* *20 mm/sec*

(a) 5-axis system (b) 4-axis system

Fig 8: Square-cut (10mmx10mm) with various cutting speeds

For the alpha design, a cutting speed of 10 mm/sec resulted in significant ringing. For the beta design, comparable imperfections occurred at cutting speeds approximately twice as fast. Correspondingly, the new design should be capable of building parts 2 times faster.

6. Conclusion

Our new CAM-LEM machine design demonstrates significant performance improvements over our alpha design. By restructuring the former 5-axis, single kinematic chain into 2, 2-axis subsystems, the resulting system is faster and more precise. While the altered inertial loads did not improve system performance, the higher structural stiffness enabled faster cutting speeds. The anticipated improvement in build speed is roughly a factor of two. In addition, the new system is less complex, due to elimination of one servoed axis and decoupling of the translation and orientation axes, and less prone to disturbances during cutting, since parts on the cutting table do not need to be reoriented. Analysis predicts that the new design will be easier to calibrate, though this has not yet been experimentally verified.

In future work, the new system will be evaluated in terms of maximum practical build speeds for representative parts. Cutting precision will be experimentally quantified. In addition, the system will be integrated with automated material handling for sheet feeding and cut-part extraction and assembly.

Acknowledgments

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7. References

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