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THE DESIGN AND MANUFACTURE OF A GEAR-COUPLED SERIAL CHAIN TO TRACE THE BUTTERFLY CURVE

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ABSTRACT

This paper presents a design and manufacturing methodology for a mechanical system that draws trigonometric curves assembled from a series of links connected by gears. We demonstrate this technique using 11 gear-coupled links that trace a butterfly curve. The equation of a butterfly curve is converted to the relative rotations of the links of a coupled serial chain assembled so it operates with one input. We present a procedure to determine the adjustments to the gear ratios and link dimensions necessary for practical manufacture of the mechanism. The results are demonstrated by a working prototype.

INTRODUCTION

This paper presents the details necessary to manufacture the system formed by a gear-coupled serial chain that traces a complex plane curve such as the "Butterfly curve" [1]. The result is a coupled serial chain where the sequence of links are connected by cable, belt or gear drive [2]. Our goal is to present the adjustments necessary to use additive manufacturing for the design of this complex mechanism. The result is a system that uses a total of 32 gears with custom gear ratios. The link geometries were developed to reduce weight and increase cross-sectional moment of inertia. Finally, a combination of acetone and a silicon lubricant were used to perform the final fitting of the revolute joints to obtain a tight clearance with minimal friction.

LITERATURE REVIEW

Krovi et al. [2, 3] provide a design methodology for single degree of freedom linkage systems formed as serial chains with joints coupled by belt and cable drives. Recent work by Liu and McCarthy [4] shows the usage of belt and cable drives to design mechanisms to trace plane algebraic curves. The use of belt and cable drives to actuate the joints of robotic hands can be found in [5–7]. Collins [8] uses a combination of cables and gears to actuate finger joints, while Lin [9] uses gears. Our approach follows Krovi, but uses gearing to provide the joint coupling.

The use of additive manufacturing for the fabrication of mechanical systems can be traced to Mavroidis [10] and Laliberte [11]. The manufacturing options include selective laser melting [12], stereolithography and selective laser sintering [13], and layer building technology [14]. Research in additive manufacturing of mechanisms generally focuses on techniques to avoid assembly [15]. In this paper, we use fused deposition modeling by the Stratasys Fortus 450mc, which requires manufacture of individual components and assembly to maintain tolerances, but is fast and inexpensive for prototype development [16].

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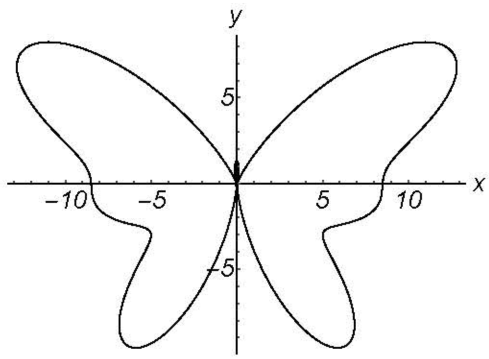

FIGURE 1. A plot of a butterfly curve of dimension ±12 cm wide

PRELIMINARIES

Liu and McCarthy [1] have shown that a trigonometric plane curve, $\mathbf{P} = (x(\theta), y(\theta))$,

$$P = \begin{Bmatrix} x(\theta) \\ y(\theta) \end{Bmatrix} = \begin{Bmatrix} \sum_{k=0}^{m} a_k \cos k\theta + b_k \sin k\theta \\ \sum_{k=0}^{m} c_k \cos k\theta + d_k \sin k\theta \end{Bmatrix}, \quad (1)$$

where a_k, b_k, c_k and d_k, $k = 0,\dots,m$, are real coefficients and $\theta \in [0, 2\pi]$, can be converted to the form,

$$P(\theta) = \begin{Bmatrix} \sum_{k=0}^{m} L_k \cos(k\theta - \psi_k) + M_k \cos(-k\theta - \eta_k) \\ \sum_{k=0}^{m} L_k \sin(k\theta - \psi_k) + M_k \sin(-k\theta - \eta_k) \end{Bmatrix}, \quad (2)$$

in which,

$$\begin{aligned} L_k &= \frac{1}{2}\sqrt{(a_k + d_k)^2 + (c_k - b_k)^2}, \\ M_k &= \frac{1}{2}\sqrt{(a_k - d_k)^2 + (c_k + b_k)^2}, \end{aligned} \quad (3)$$

and

$$\psi_k = \arctan\frac{c_k - b_k}{a_k + d_k}, \quad \eta_k = \arctan\frac{c_k + b_k}{a_k - d_k}. \quad (4)$$

The result is an equation that can be interpreted as a sequence of links driven at a prescribed set of speed ratios $k = 1,\dots,m$ to trace the curve. Equation 3 defines the lengths of the links L_k and M_k and (4) defines the phase angles ψ_k and η_k of their movement.

BUTTERFLY CURVE

When the equation of the Butterly curve [17],

$$\begin{aligned} P_B:\ \rho(\theta) =& 7 - \sin\theta + 2.3\sin 3\theta + 2.5\sin 5\theta - 2\sin 7\theta \\ & - 0.4\sin 9\theta + 4\cos 2\theta - 2.5\cos 4\theta, \end{aligned} \quad (5)$$

is written in the form of (2), we obtain the link lengths and phase angles listed in Table 1. The $k = 0$ row defines the ground pivot position. There are totally 14 links consisting the coupled serial chain to generate the butterfly curve shown in Figure 1.

TABLE 1. Speed ratios, link length ratios and phase angles for the butterfly curve

k	L_k	ψ_k	M_k	η_k
0	0.25	$-\pi/2$	0.25	$-\pi/2$
1	7	0	2	0
2	0.5	$\pi/2$	1.15	$\pi/2$
3	2	0	1.25	π
4	1.15	$-\pi/2$	1.25	$\pi/2$
5	1.25	π	0	0
6	1.25	$-\pi/2$	1	$-\pi/2$
7	0	0	0	0
8	1	$\pi/2$	0.2	$-\pi/2$
9	0	0	0	0
10	0.2	$\pi/2$	0	0

This is the starting point for the design of our mechanism. In what follows, we adjust these dimensions to facilitate manufacture using Additive Manufacturing.

DESIGN MODIFICATIONS

The build envelope of the Stratasys Fortus 450mc additive manufacturing system is $406 \times 355 \times 406$ mm, which sets a limit to the size of our mechanism. Our experiments showed that the smallest feature size that we could reliably generate was a 10mm hole for the link joints. This restricted the size of our gears to a minimum diameter of 15mm, which in turn sets our minimum link dimension to be 20mm.

If the dimension of the smallest link in Table 1 to be 20mm, the longest link must be 700mm, which is beyond the build envelop of the Stratasys Fortus printer. If we eliminate the three shortest links, we can reduce the size of the largest link to 210mm. Specifically, we delete the links denoted as L_2, L_{10} and M_8. The resulting Butterfly curve differs from the original curve by a maximum of 21.6mm, see Figure 2. The dimensions for manufacturing prototype are listed in Table 2. This removes the high frequency terms, which reduces the curvature and softens the curve.

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TABLE 2. Speed ratios, link length ratios and phase angles for the manufacturing prototype

k	L_k	ψ_k	M_k	η_k
0	0.25	$-\pi/2$	0.25	$-\pi/2$
1	7	0	2	0
2	0	0	1.15	$\pi/2$
3	2	0	1.25	π
4	1.15	$-\pi/2$	1.25	$\pi/2$
5	1.25	π	0	0
6	1.25	$-\pi/2$	1	$-\pi/2$
7	0	0	0	0
8	1	$\pi/2$	0	0
9	0	0	0	0
10	0	0	0	0

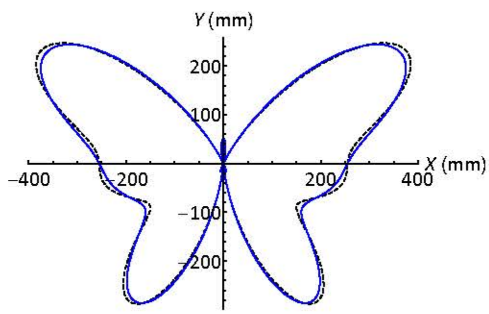

FIGURE 2. The Butterfly mechanism is to draw a curve ± 40 cm wide (solid line). Using 11 links in the coupled serial chain introduces variations from the original 14 link version (dashed line)

DRIVE TRAIN

The drawing mechanism for trigonometric curves uses pairs of links that rotate in opposite directions [1]. The speed ratio for each link in the chain is given by $+k$ for links L_k and $-k$ for links M_k. This speed ratio is measured relative to the world frame. By introducing relative speed ratios at each link, we can simplify the construction of the mechanism using gear trains.

The drawing mechanism consists of a sequence of joints G_j and links B_j, $j = 1,\ldots,11$ connected in series and attached by joint G_1 to a base, Figure 3. Each link B_j has a gear fixed to the link and centered on its joint G_j, which for convenience we call G_j as well. This joint includes a bearing that engages the axle mounted on the previous link B_{j-1}. The link B_j has an axle at the end opposite to joint G_j that engages the bearing of G_{j+1} on link B_{j+1}.

Each joint G_j includes a second gear D_j that is rigidly mounted to the axle of previous link B_{j-1}. Similarly, the axle at the other end of link B_j engages and is fixed to the gear D_{j+1}. The drive system consists of a sequence of connections between gear D_j and the gear G_{j+1}. To start, D_1 is rigidly mounted to an axle attached to the base, and the mechanism is actuated by a drive gear that engages G_1.

This configuration allows us to define the relative speed ratios between the gears D_j and G_{j+1} when the link B_j is held fixed,

$$\frac{\omega_{j+1,j}}{\omega_{j-1,j}} = \frac{T_{D,j}}{T_{G,j+1}}, \tag{6}$$

where $T_{D,j}$ and $T_{G,j+1}$ are the teeth number of the gear D_j and G_{j+1}.

The relative speed ratios are related to world frame speed ratios listed in Table 2, by

$$\omega_{j+1,j} = \omega_{j+1} - \omega_j, \tag{7}$$

therefore the relative speed ratio are given by,

$$\frac{\omega_{j+1,j}}{\omega_{j-1,j}} = \frac{\omega_{j+1} - \omega_j}{\omega_{j-1} - \omega_j}. \tag{8}$$

From these equations, we calculate the gears that provide the world frame speed ratios that we need.

Figure 3 shows the structure of a serial chain consisting of three links. The gear D_1 is rigidly attached to the base. Link B_1, B_2 and B_3 have gear G_1, G_2 and G_3 fixed to them respectively. The relative rotation is achieved by adding chain driven between gear D_1 and G_2, and between gear D_2 and G_3. The resulting mechanical system has a single degree of freedom.

In the chain driving configuration, we assume the links are lined up with one counter-clockwise rotating link followed by one clockwise rotating link. The world frame is built along the base. In the world frame, we denote the angular velocities of link B_j and gear G_j as ω_{Bj} and ω_{Gj}, respectively. It is obvious that $\omega_{Bj} = \omega_{Gj}$. We use the denotation ω_{Dj} for the angular velocity of gear D_j. From Table 2, we have the speed ratios for all the links.

Figure 4 shows the angular velocities of the components that drive the first two links in the world frame. The gear D_1 is static relative to the world frame thus $\omega_{D1} = 0$. Reference frame 1 is built along link B_1. Figure 5 shows the angular velocities of the components in reference frame 1. We denote the teeth number of the gear D_j and G_j as $T_{D,j}$ and $T_{G,j}$, respectively. Thus we can calculate the ratio of the teeth number between gear D_1 and G_2 as

$$\frac{T_{D,1}}{T_{G,2}} = \frac{\omega'_{G2}}{\omega'_{D1}} = \frac{\omega_{B2} - \omega_{B1}}{-\omega_{B1}} \tag{9}$$

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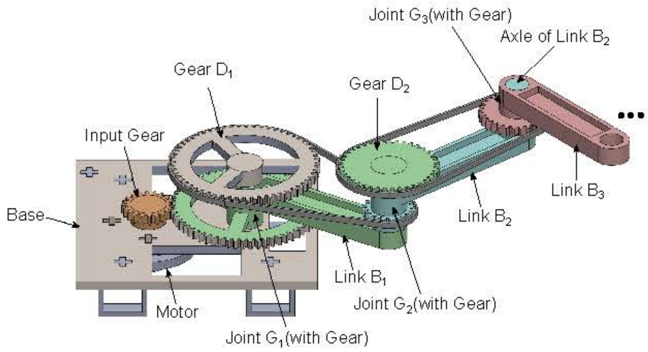

FIGURE 3. The structure of a coupled serial chain consisting of three links

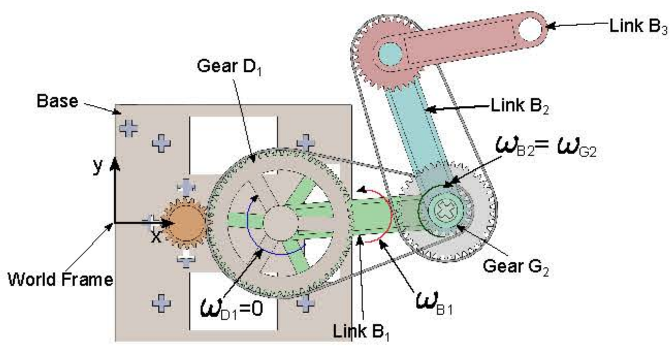

FIGURE 4. The angular velocities of the components for the first two links in the world frame

Figure 6 and Figure 7 show the angular velocities of the driving components from link B_2 to link B_3 in the world frame and reference frame 2, respectively. Similarly, we can calculate the relative size of gear D_2 and G_3 as

$$\frac{T_{D,2}}{T_{G,3}} = \frac{\omega'_{G3}}{\omega'_{D2}} = \frac{\omega_{B3}-\omega_{B2}}{\omega_{B1}-\omega_{B2}} \tag{10}$$

Therefor the equation to calculate the relative size of gear

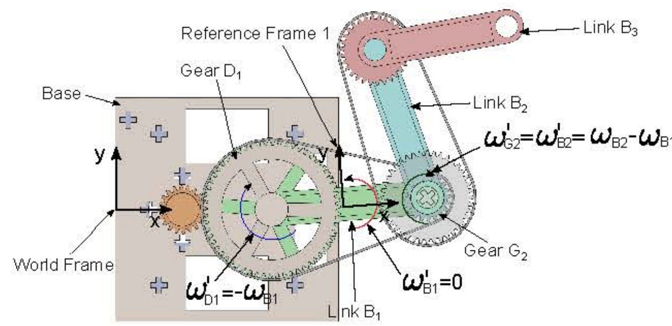

FIGURE 5. The angular velocities of the components for the first two links in the reference frame 1

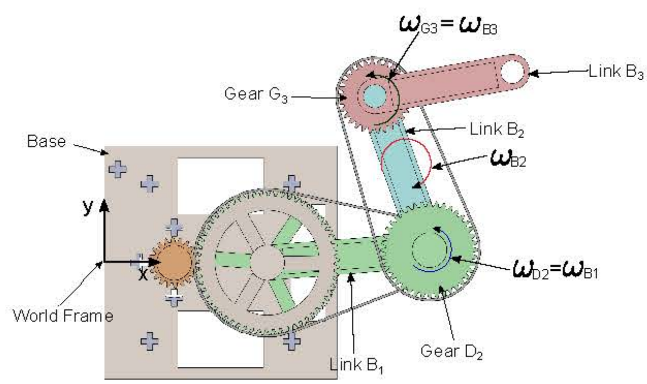

FIGURE 6. The angular velocities of the driving components from link B_2 to link B_3 in the world frame

D_j with respect to gear G_{j+1} can be obtained as

$$\frac{T_{D,j}}{T_{G,j+1}} = \frac{\omega'_{G(j+1)}}{\omega'_{Dj}} = \frac{\omega_{B(j+1)}-\omega_{B(j)}}{\omega_{B(j-1)}-\omega_{Bj}} \tag{11}$$

THE COUPLED SERIAL CHAIN MECHANISM

In this section, we present the methodology of using relative rotation to build a coupled serial chain mechanism that can trace the butterfly curve showing in solid line in Figure 2. The resulting mechanism has a single degree of freedom. Recall that we have eleven links in our manufacturing version of coupled serial chain. The column k in Table 2 defines the speed ratios for all the

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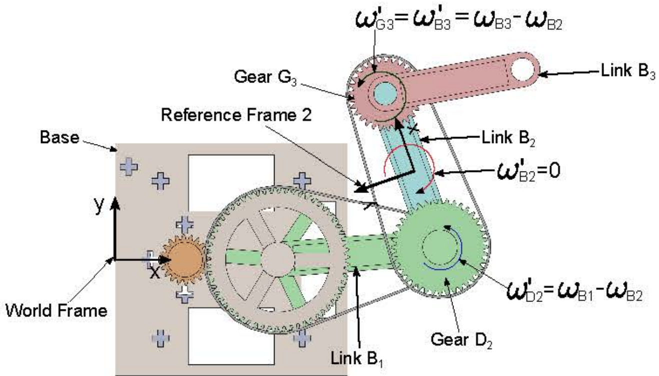

FIGURE 7. The angular velocities of the driving components from link B_2 to link B_3 in the reference frame 2

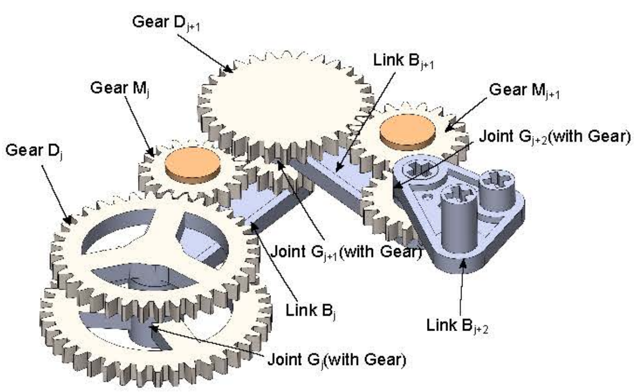

FIGURE 8. The configuration of gear driving from Link B_j to Link B_{j+2}

links. The ground pivot position is given by the $k=0$ row in Table 2. We have six links that rotate counter-clockwise are L_1, L_3, L_4, L_5, L_6 and L_8, and another set of five links rotate clockwise are M_1, M_2, M_3, M_4 and M_6. In our configuration, we line up all the links from the longest to the shortest according to their length S_j. Additionally, the links are assembled in a way such that the counter-clockwise rotating links are followed by a clockwise rotating link and vice versa. Therefore, the sequence of the eleven links in the serial chain is $L_1, M_1, L_3, M_3, L_5, M_4, L_6, M_2, L_4, M_6$ and L_8. The links in this sequence are denoted as B_j $(j = 1 \cdots 11)$ and the associated phase angle for each link is denoted as δ_j.

Rather than a chain driven, we introduce an alternative method of driving the mechanism to include a middle gear M_j

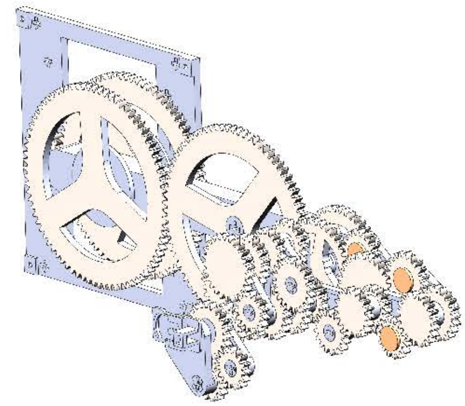

FIGURE 9. The solid model of the Butterfly mechanism to be built using additive manufacturing

between gear D_j and G_{j+1}. We replace the links with plates and locate the middle gear M_j a position such that its pitch circle is tangent to the pitch circles of both the gear D_j and G_{j+1}. Figure 8 shows the configuration the components from link B_j to link B_{j+2}. Note that in order to keep the relative rotation speed, the middle gear M_j has to be the same size as gear D_j or the G_{j+1}. The teeth number of the gear M_j is denoted as $T_{M,j}$.

By applying (11), we can obtain the relative size of the gear D_j and G_{j+1}. We make the module of all the gears to be m. The addendum of the gear is denoted as a. In order to make the three gears assembled on each plate mesh correctly, the following two conditions must be satisfied, such that

$$\frac{m}{2}(T_{D,j} + T_{G,j+1}) + 2a < S_k \tag{12}$$

$$\begin{aligned} &\frac{m}{2}(3T_{D,j} + T_{G,j+1}) \geq S_k \quad or \\ &\frac{m}{2}(T_{D,j} + 3T_{G,j+1}) \geq S_k \end{aligned} \tag{13}$$

Equation 12 makes sure the gear D_j and G_{j+1} do not conflict with each other. Equation 13 guarantees that the gear D_j, M_j and G_{j+1} are close enough to mesh with each other correctly. In our model, we choose the gear module $m = 1.5$ and addendum $a = 1.5$mm. We make the length of the smallest link to be 30mm. The dimensions for all the components are listed in Table 3. The manufacturing model of our linkage is shown in Figure 9. The simulation of the motion of our mechanism is shown in Figure 10.

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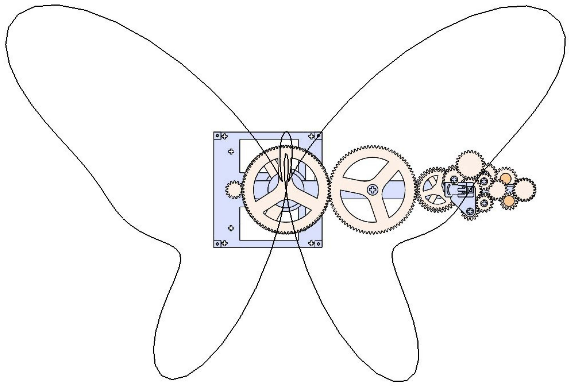

FIGURE 10. Simulation of the end-effector movement of the Butterfly mechanism using *SolidWorks Motion Analysis*

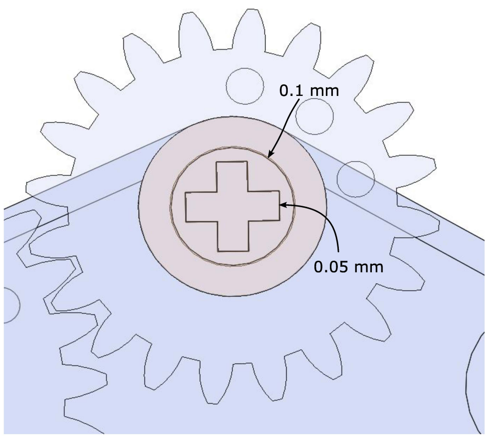

FIGURE 11. Dimensional differences for mounting features for gear and link axle are specified to be less than the resolution of the Fortus 450mc system. The parts are manually fit to ensure performance

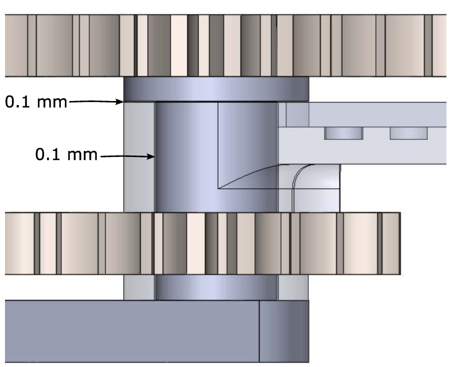

FIGURE 12. Dimensional differences between assembly features is less than the resolution of the Fortus 450mc system, therefore manual fit is required

TABLE 3. Manufacturing dimensions of the single coupled serial chain to draw the butterfly curve

j	k	B_j	S_j	δ_j	$T_{D,j}$	$T_{M,j}$	$T_{G,j+1}$
1	1	L_1	210	0	80	80	40
2	-1	M_1	60	0	36	18	18
3	3	L_3	60	0	30	20	20
4	-3	M_3	37.5	π	20	15	15
5	5	L_5	37.5	π	18	16	16
6	-4	M_4	37.5	$\pi/2$	20	18	18
7	6	L_6	37.5	$-\pi/2$	16	20	20
8	-2	M_2	34.5	$\pi/2$	15	20	20
9	4	L_4	34.5	$-\pi/2$	25	15	15
10	-6	M_6	30	$-\pi/2$	21	15	15
11	8	L_8	30	$\pi/2$	0	0	0

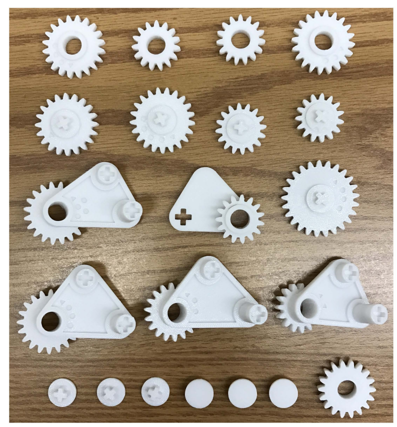

FIGURE 13. Example of the Butterfly mechanism drive components manufactured by the Fortus 450mc system.

PHYSICAL PROTOTYPE

We used the Stratsys Fortus 450mc additive manufacturing system to build all the components for our linkage. These include 11 links, 32 gears, ground pivot and the input crank. The resolution of the Stratsys printer is 0.127 mm. Through repeated experimentation, we sized the clearance between the revolute joint and the pivot to be 0.1 mm. An acetone and silicon combination solution was used to simultaneously wear the size of joint pin and hole to a tight tolerance while lubricating the contact surface to minimize friction. In order to ensure the cap gear tightly assembled to the link joint, the clearance fitting was tested and determined to be 0.05 mm. The clearance between components is shown in Figure 11 and Figure 12.

We manufactured all the components individually and assembled them together to obtain our serial coupled serial chain

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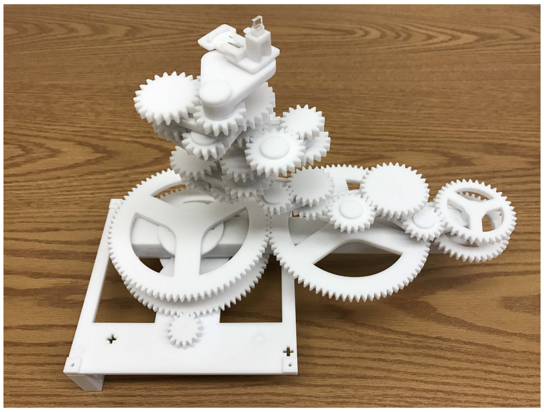

FIGURE 14. The fully assembled Butterfly mechanism

that can trace the butterfly curve. Part of the components are shown in Figure 13. The final manufactured prototype is shown in Figure 14.

CONCLUSION

This paper presents the manufacturing details for the construction of complex systems to draw trigonometric curves using additive manufacturing. The method is demonstrated for the 14 link Butterfly curve, which must simplified to an 11 link system to fit the requirements of the Stratasys Fortus system. We show how to adjust the dimensions of the gears to accomplish the desired joint movement within the tolerances available to this manufacturing process. The result is a functional prototype butterfly linkage drawing mechanism. Future work will simplify design and improve the manufacturing quality of these systems.

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