Proceedings of DETC'01
ASME 2001 Design Engineering Technical Conferences and Computers and Information in Engineering Conference
Pittsburgh, Pennsylvania, September 9-12, 2001

DETC2001/DAC-21087

DESIGN OF PASSIVE RECONFIGURABLE MANIPULATION ASSISTIVE AIDS

Xichun Nie
Department of Mechanical Engineering
Center for Intelligent Machines
McGill University
3480 University Street, #421
Montreal, Quebec, Canada, H3A2A7
email: xnie@cim.mcgill.ca
Web: http://www.cim.mcgill.ca/~xnie

Venkat Krovi
Department of Mechanical Engineering
Center for Intelligent Machines
McGill University
3480 University Street, #421
Montreal, Quebec, Canada, H3A2A7
email: venkat@cim.mcgill.ca
Web: http://www.cim.mcgill.ca/~venkat

ABSTRACT

Multi-jointed mechanical systems typically possess excess degrees-of-freedom, which often are neither required nor used in performing typical manipulation tasks. These excessive degrees of freedom then need to be reduced by application of constraints, either actively by suitable control or passively in hardware, prior to task performance.

Our interest is in creating articulated manipulation assistive aids, which combine the motion flexibility due to the multiple articulations with the simplicity of reduced degree-of-freedom control and actuation due to the presence of hardware mechanical constraints.

Specifically we investigate the process of design and prototyping of such reduced-degree-of-freedom manipulators to closely approximate desired planar paths. We then examine design enhancements to permit easy reconfiguration for different sets of paths. Finally, special attention is paid to the creation of a prototype with the ability to be reconfigured for multiple sets of paths, by a controlled variation of the principal structural parameters.

Keywords: *Reconfigurable prototype, Manipulation assists, closed planar paths, kinematic synthesis, Fourier methods, optimization.*

INTRODUCTION

Our interest is in the typical manipulatory tasks performed by humans in many industrial settings. Passive manipulation assistive aids, that can interact with and augment the manipulation skills of humans, have applications in diverse arenas from manufacturing assembly lines to rehabilitation engineering.

Many of the typical tasks performed by humans are low-dimensional (one or two degree-of-freedom (d.o.f)) motions along trajectories or surfaces while subjected to external loads. For example, a curve on a planar surface can be easily recognized as a one-dimensional constraint surface, parameterizable by a single parameter such as arc-length, in a higher dimensional task-space. In this paper, we will focus on the design of passive, articulated, manipulation-assistive aids that can either work in cooperation with the human operator or provide a low cost automation solution for the task of tracing such one-dimensional closed-loop curves in the plane.

Articulated devices are typically composed of rigid links linked together with simple joints formed from lower kinematic pairs. Since, each lower kinematic pair introduces one degree-of-freedom to the motion of the end-effector, theoretically, an articulated device with just *one joint* is adequate to trace any desired curve. For simple tasks, such as tracing straight lines or circles, mechanical aids with one d.o.f, such as slides and compasses, have traditionally been used to aid the task performance. Further, the users have typically relied on the structural stability of such mechanical assistive aids to enhance the task performance, by restricting and redirecting the aspects of the user's motions and forces.

However, the geometric motion capability of the end-effector of an articulated device with a single lower-kinematic-pair joint tends to be restricted. Multi-jointed articulated systems become necessary to provide adequate flexibility to trace more complex curves. However, this comes at the price of increasing the number of degrees of freedom, which need to be eliminated by application of either *active software-based* or *passive hardware-based constraints*, in order to perform the single degree-of-freedom curve-tracing task.

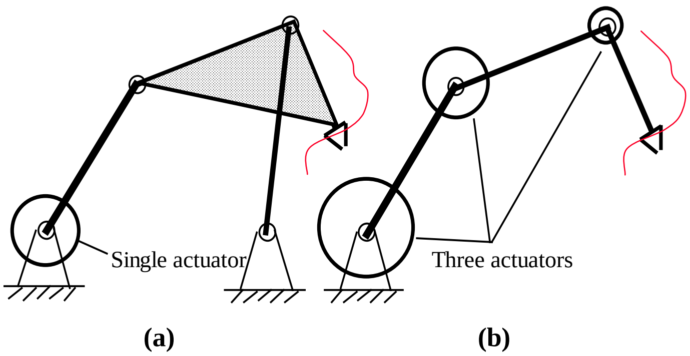


Figure 1: Constraint implementation in an articulated linkage to trace a one-dimensional curve: (a) Passive hardware-based (loop-closure) in a four-bar linkage and (b) Active software-based (coordinated-control) in a robot.

A good example of the software-based constraint implementation is seen in a multi-jointed robotic manipulator required to trace a fixed curve, such as in an arc-welding application. The constraints take the form of requirement to coordinate the joint motions, in accordance with the inverse kinematics solution, to ensure that the end effector can trace the given curve. This coordination, performed in software, is then realized using the multiple independent electromechanical actuators with the benefits of: (i) increased flexibility of reconfiguration to tackle a variety of tasks through software reprogramming; and (ii) relative simplicity of mechanical design since the functionality is now provided by electronic control components. On the other hand, such systems require high performance actuators and coordinated control at sufficient large control bandwidth to meet task performance requirements. Further, in many industrial applications such as automotive assembly lines, the flexibility for reconfiguration tends to be rarely exploited.

Alternatively, constraints could also be implemented in hardware, as seen in traditional closed loop linkages. In these cases, the constraint implementation takes the form of the requirement for loop closure. For example, the four-bar linkage has four articulations and three loop closure constraints which reduce the overall degrees of freedom of the linkage to one. Such “hardware-based constraint implementations”, well known traditionally as mechanism solutions, offer distinct advantages in terms of: (i) improved reliability; (ii) excellent repeatability; (iii) passivity/stability of the constraint implementation; and (iv) low development and maintenance costs. However, as Kota and Erdman [1] note, the overall reduced usage of such hardware-constrained articulated linkages is partially due to the difficulties in the design of such mechanisms as the complexity of the task increases and the limited ability to reconfigure them easily to new sets of tasks.

We note that hardware-based motion and force constraints can also be created by *mechanically coupling the joint rotations* of a multi-joint articulated linkage. *Coupled Serial Chain mechanisms* [2] are a novel class of manipulators formed by physically coupling the distal joint rotations of a multi-link serial chain to their proximal joint rotations, using either cable/pulley drives or gear trains as shown in Figure 2(a). Each hardware coupling between distal and proximal joints reduces a degree of freedom and repeated coupling reduces the overall degrees of freedom to 1. The resulting Single Degree-of-freedom Coupled Serial Chain (SDCSC) mechanism requires only a single actuator at the base to drive the entire system, which simplifies both actuator as well as the control system design.

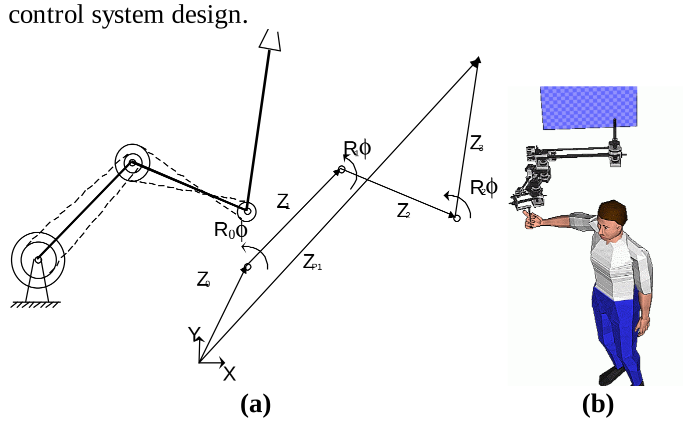


Figure 2: (a) Single Degree-of-freedom Coupled Serial Chain (b) Potential use of such passive manipulation assist devices in an industrial settings.

Such SDCSC mechanisms can be used to realize a broad range of end-effector trajectories using a single degree of freedom. Hunt [3] notes that there is no limit to the possible arrangements when gears and bands are used, especially when using non-circular gears or band wrapping profiles. Increasing the number of links enables us to trace curves of increasing complexity and variety while retaining the single degree of freedom operation. Thus, SDCSC mechanisms combine the advantages of simplicity of single-degree-of-freedom design and control of closed loop linkages with the modularity and anthropomorphic reach of serial chains.

In this paper, we will investigate the design and development of manipulation aids based on the SDCSC configuration for planar closed-loop path-following tasks. We also examine the process of enhancing the design by permitting all the structural parameters for a given SDCSC mechanism, such as link lengths, coupling ratios and initial posture, to be adjustable. The controlled adjustment of any of the above-mentioned structural parameters, termed *mechanism reconfiguration*, will be guided and facilitated by design software tools that we are developing as will be discussed later.

Figure 2(b) depicts a potential industrial application of such a manipulation assist device where the end-effector can be used to form a *passive virtual guide rail* to constrain the motions of the user to the prescribed task-space curve while retaining *the* ability to be reconfigured to realize various other constrained motions.

Organization

In Section 2, we provide a brief background on the applications of such manipulatory assistive aids before presenting an overview of the systematic design and issues pertaining to reconfigurability in Section 3. We then present details of the conversion of the design into a physical reconfigurable prototype in Section 4, prior to a short discussion of present and ongoing work in Section 5.

LITERATURE REVIEW

Software-based coordination of actively-controlled joint servo-motors of such robotic manipulators can be used to create motion and force constraints to aid human task performance. Kazerooni and Guo [4], studied “human extenders”, a class of robot manipulators worn by humans, that could provide the user with manipulability-augmentation and/or power-augmentation. However, it is important to note that the effectiveness of such software-based active constraint-implementation is limited by the dynamic response bandwidth and stability of the electromechanical systems used to implement them. Specifically the discrete sampling, delays in the data acquisition and control have the potential to introduce limit cycling that can add energy to the system and destabilize it [5]. Hence, the use of actively powered robotic systems in close proximity of human users tends to be undesirable from the viewpoint of safety.

However, in several applications, the human user is required to remain in direct intimate mechanical contact with the proposed devices in order to retain the kinesthetic and tactile perception that can aid the performance of the task significantly. The renewed interest in passivity of assistive aids that are in physical contact with the human user in such diverse areas as haptic displays, medical robotics [6], robot aided exercise therapy [7] and exercise machines [8] also motivates creation of such devices.

Li and Horowitz [8] sought to design active feedback control systems that appear passive in its interaction while executing a desired behavior specified by a velocity/force field. Other passive robotic systems such as P-TER, for Passive Trajectory Enhancing Robot [9] and PADyC, for Passive Arm with DYnamic Constraints [6] use software-based coordination of passive electromechanical brakes/ clutches (instead of active motors) at the joints to implement the constraints. While overcoming some of the stability issues, the effectiveness of the constraint implementation still remains limited by the dynamic response bandwidth of the electromechanical brakes/clutches. In contrast, constraint implementation by means of passive mechanical devices has inherent advantages over active implementations in regards to stability, response rapidity and physical robustness [10].

In recent years, a novel class of assistive devices called COllaborative roBOTS (cobots) [11] have been developed for direct physical collaboration with a human operator with shared control of tool motion. Their primary purpose is not to enhance human strength, but to assist the human operator to constrain and guide the motions and forces. The operator supplies all motive power while these assistive devices enforce mechanically created yet configurable guiding surfaces, or constraints.

The manipulation assistive aids we are developing share many features with these cobots. Moore [12] proposed a three-link serial-chain cobot where each pair of consecutive joints has their rotations coupled by a computer controlled continuously variable transmission (CVT) effectively constraining the cobot’s end point to a particular trajectory through space. However, they do not consider the ability to control the variation of other structural parameters such as link-lengths or discuss methods for selection of the parameters that would enable realization of a specific constraint. Further, in employing a “non-holonomic CVT” based on a central transmission sphere supported between the drive rollers, forces perpendicular to the constraint can only be resisted upto the limit of Coulomb friction. In our work, we implement the coupling using cable and pulley drives which permit much higher end-effector forces to be sustained.

In other background on adjustable linkages, many examples (such as the adjustable stroke-length Whitworth quick return mechanism) exist for situations where the overall size and geometric variation is limited. In recent years, the design of mechanisms with multiple explicitly adjustable structural parameters, to serve as an intermediate between the overly flexible “robotic manipulators” and relatively inflexible “mechanisms” is also regaining research interest. Past attempts include adjustable mechanisms with applications in flexible assembly systems [13] and “adjustable/programmable robotic mechanisms” (ARMS) [14].

While many elegant software tools (ADAMS and WORKING MODEL) aid the designer in the kinematic and dynamic analysis of complex mechanisms, fewer synthesis software design tools exist. Erdman [15] reviews the state-of-the-art in computer-aided design-synthesis of mechanisms noting that the software design tools cover only a small portion of the immense variety of feasible mechanisms. Few examples exist of the use of GUI capabilities to enhance the human-machine interface to aid the specification of task requirements and conveying the results of the design of the mechanism back to the designer such as SphinxPC [15] or LINCAGES [15].

DESIGN SYNTHESIS METHOD

As noted in the previous section, the presence of the hardware constraints, while bringing about a reduction in the degrees of freedom, creates a need for such devices to be customized for specific tasks for optimal performance. A careful characterization of the tasks and task-specific customization of the device in the *design* is critical because once configured, the designed end-effector motions cannot be altered easily.

In contrast to trial and error methods or simulation/analysis methods, we will focus on determination of the dimensions of the device to satisfy a set of design specifications by *design synthesis*. Further, we will explore enhancing the flexibility of reconfiguration of such manipulators, to perform multiple sets of tasks by adjustment and control of the *principal structural parameters*. Such an implementation of user-programmable passive hardware constraints would permit the resulting passive articulated assistive aids to regain some of the versatility of robotic manipulators.

In this process, we consider: (i) classification of the desired planar task curves into families; (ii) determination of the numeric values of parameters of the nominal mechanism; and (iii) determination of the required range of variation of the parameters in order to achieve *multiple sets* of desired tasks. A design environment was developed to aid the designer in the selection of suitable values for the parameters of the device. Integration of tools from CAD modeling, customization to the user, interactive refinement using virtual prototyping to aid a rapid transition to final detailed designs and fabrication are explored.

Fourier-based Optimal Kinematic Synthesis Method

Pang and Krovi [17] explored the development of alternative method for synthesis of SDCSC mechanisms for planar path following tasks, using tools from Fourier analysis and optimization. *This process is briefly summarized here and the reader is referred to [17-18] for further details.*

At this stage, we would like to make a couple of important observations. First, in this implementation, the desired paths are required to be planar *closed-loop* curves. This does not pose too severe a restriction since an open-loop curve may be treated as being a part of a closed-loop curve. However, several candidates for the closed-loop curves may exist and the process of selection of the "most suitable" candidate closed-loop curve is beyond the scope of this paper. Second, while closely allied to the traditional optimization-based synthesis methods, the proposed method employed a novel energy-based objective function with the optimization being performed over a set of non-mechanism parameters.

Figure 2(a) shows a typical three-link SDCSC mechanism at its initial configuration with various relevant parameters defined. In general the forward kinematic equation of an *M*-link SDCSC mechanism can be written in the complex number format as:

$$Z_P(\phi_j) = Z_0 + Z_1\, e^{iR_0\phi_j} + Z_2\, e^{iR_1\phi_j} + \ldots + Z_M\, e^{iR_{(M-1)}\phi_j} \qquad (1)$$

where $\|Z_k\| = L_k$ is the length of the k^{th} link and $\angle Z_k = \Theta_k$ represents the posture angle of the k^{th} link at the first location and $Z_k = L_k\cos(\Theta_k) + i\,L_k\sin(\Theta_k)$ denotes the complex vector from the center of the proximal joint to the center of the distal joint of the k^{th} link at the 1^{st} configuration. The complex number equation in Eq. (1) can be rewritten in scalar form as two loop-closure equations giving the discrete positions of the end effector, x_j and y_j, as a function of ϕ_j, the input link rotation angle relative to the initial position as:

$$\begin{aligned} x_j = x(\phi_j) &= L_0\cos(\Theta_0) + L_1\cos(\Theta_1 + R_0\phi_j) + \\ &\quad \ldots + L_n\cos(\Theta_M + R_{(M-1)}\phi_j) \\ y_j = y(\phi_j) &= L_0\sin(\Theta_0) + L_1\sin(\Theta_1 + R_0\phi_j) + \\ &\quad \ldots + L_n\sin(\Theta_M + R_{(M-1)}\phi_j) \end{aligned} \qquad (2)$$

Our overall goal is to determine the smallest number of links (and their dimensions/initial configurations) of an SDCSC mechanism to perform a desired *path following* task. The task itself is specified as a set of N discrete path points along a given path, $\bar{z}[n] = \bar{x}[n] + i\,\bar{y}[n] \quad \forall\ 1 \le n \le N$.

The Discrete Fourier Transform has traditionally been used in the signal processing to transform a finite length sequence of a uniformly sampled periodic signal, $z[j]$, into a sequence of Fourier coefficients in the frequency domain, denoted as $Z[k]$, as shown below.

$$Z[k] = DFT\left[z[j]\right] = \sum_{j=1}^{N} z[j]\, e^{\frac{-i2\pi(k-1)(j-1)}{N}} \qquad (1 \le k \le N) \qquad (3)$$

Various coefficients may be computed as:

$$a_0 = \frac{2Z[1]}{N},\ a_k = \frac{2\,\mathrm{Re}\,(\mathrm{Z}[k+1])}{N},\ b_k = \frac{2\,\mathrm{Im}\,(\mathrm{Z}[k+1])}{N}$$

and then be used in the synthesis equation to reconstruct the original signal as a finite trigonometric series:

$$z[j] = a_0 + \sum_{k=1}^{N/2} [a_k\cos(\frac{2\pi\,k\,j}{N}) + b_k\sin(\frac{2\pi\,k\,j}{N})] \qquad (4)$$

Our design method exploits the fact that the forward kinematics equations, Eq. (1), take the form of a finite trigonometric series in terms of the input crank rotations paralleling Eq. (4). The extracted coefficients from the DFT output, $Z[k]$, can now be readily interpreted in terms of the link lengths, L_k, coupling-ratios, R_k and the initial configuration, Θ_k, of the SDCSC mechanism which can trace the given path as:

$$L_k = \sqrt{{a_k}^2 + {b_k}^2},\ R_k = \frac{2\pi\,k\,j}{N},\ \Theta_k = \tan^{-1}(\frac{b_k}{a_k}) \qquad (5)$$

While all terms of the DFT output, $Z[k]$, are required for an *exact* reconstruction of the input data sequence, $\bar{z}[n]$, the design method exploits the fact that the greatest contribution to the reconstruction comes from the largest peaks in the DFT output. Hence, selecting a small number of the largest peaks ($M << N,\ M \approx 3$) could still permit reconstruction of a *good approximation* of the input data.

However, in typical path-following problems, the set of path points, $\bar{z}[n]$, is specified without an input crank parameterization $\phi[n]$ in one-to-one *correspondence* with each path point. This selection is left to the discretion of the designer, often without any specific guidelines. The sole requirement is one of monotonicity of the parameterization. Upon selection of a suitable candidate parameterization, $\phi[n]$, the set of N data points, $\bar{z}[n]$ may be uniformly resampled and input to the DFT algorithm. However, it is important to note that the parameterization of the input data plays a critical role in determining the number of significant terms in the DFT output. Hence to aid the designer in the suitable selection of $\phi[n]$ an optimization scheme was developed.

Thus, the overall goal of the Fourier-based optimization method is one of determining a suitable input crank angle parameterization, which minimizes the error in reconstruction of the input data by a finite trigonometric series with M terms. In mechanism synthesis terms, this would then be equivalent to determine the values of the relevant link parameters of an *M-link* SDCSC mechanism that can closely approximate a desired path.

Software Implementation

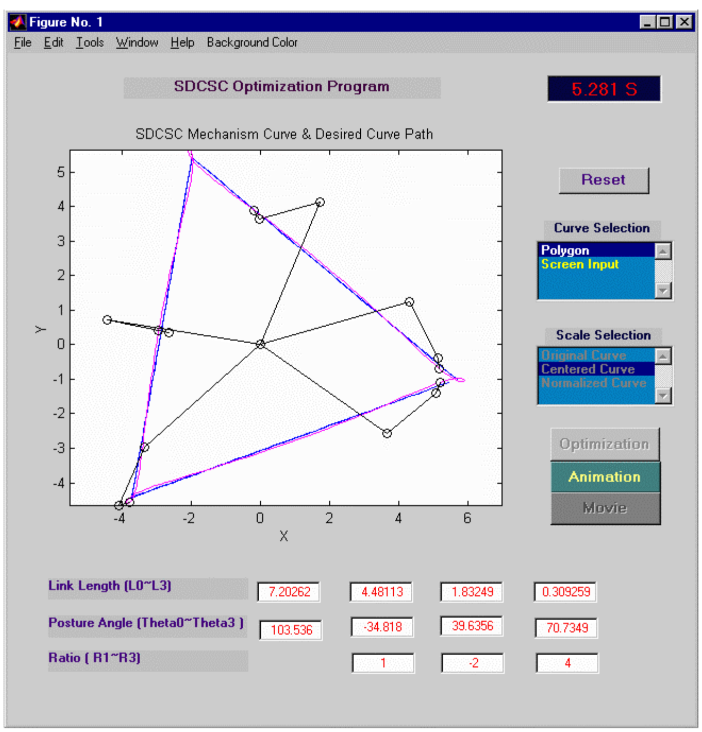


Figure 3: Sample Graphical User Interface (GUI) windows depicting the synthesis process for desired triangular end-effector path.

This synthesis method was implemented in the form of a MATLAB-based software package. One distinguishing feature of this method is that the synthesis process can be completed in seconds, taking advantage of the speed of the signal processing algorithms, such as the FFT. Further, in contrast to traditional mechanism synthesis methods, all the parameters defining the optimal SDCSC mechanism (the link lengths, coupling ratios between every two adjacent joints and initial posture angles for each link) are determined simultaneously.

A Graphical User Interface (GUI) was developed and used to enhance the ability of the designer to interact with this synthesis in an intuitive manner with this software package. The GUI interface permits the user to: (i) specify, save and manage the desired task specifications (as polygonal paths or by clicking on the screen from the user interface); (ii) display and animate multiple assembly configurations; and (iii) parametrically link to other CAD and control software to propagate the results of the synthesis.

Curve Normalization

In our work, we would like to reconfigure the SDCSC mechanism to trace a variety of curves by a controlled variation of the principal structural parameters. We investigated a method of classification of the curves into families and to determine the relationship between the members of a single family and the principal structural parameters.

To this end, we adopt and extend the approach of curve-normalization, outlined in [19]. The principal idea behind curve normalization is to scale, rotate and reposition any arbitrary curve to a standard position so that comparison with other normalized curves will be possible. The standard position, is selected such that the centroid coincides with the origin of the world coordinate system, and the original curve is scaled so that the maximal radius vector is 1 unit and aligned along the positive X axis.

A three-step procedure is employed for curve normalization: (i) The centroid of the given data (X and Y) is calculated and the original curve moved to align the centroid with the origin of the world coordinate system; (ii) The magnitude of maximal radius vector (R_{max}) is determined and the entire curve is normalized with the scale factor ($S = 1/R_{max}$) and (iii) The scaled curve is rotated by an angle α, so as to align the maximum radius vector with the positive X-axis. The three steps in this process can be combined and represented as a homogenous transformation in matrix format as:

$$\begin{bmatrix} P_{nx} \\ P_{ny} \\ 1 \end{bmatrix} = \begin{bmatrix} S\cos\alpha & S\sin\alpha & -X \\ -S\sin\alpha & S\cos\alpha & -Y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} P_x \\ P_y \\ 1 \end{bmatrix} \tag{6}$$

where,

$P_x,\ P_y$: x and y coordinates of the desired curve.

P_{nx}, P_{ny} : x and y coordinates of the normalized curve.

X, Y : Coordinates of the centroid of the original desired curve.

S : Scale factor for normalization ($S = 1/R_{max}$)

α : Angle measured from the positive X axis to the maximum radius vector prior to rotation.

Thus, upon normalization, any randomly positioned curve can now be circumscribed by a circle of radius 1, centered at the origin, making it convenient for curve comparison. In the context of curves generated by the end-effector of the SDCSC mechanism, Eq. (6) can also be rewritten as:

$$\begin{bmatrix} P_{nx} \\ P_{ny} \\ 1 \end{bmatrix} = \begin{bmatrix} S\cos\alpha & S\sin\alpha & -X \\ -S\sin\alpha & S\cos\alpha & -Y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L_0\cos\Theta_0 + \sum_{k=1}^{M} L_k \cos(\Theta_k + R_{k-1}\phi) \\ L_0\sin\Theta_0 + \sum_{k=1}^{M} L_k \sin(\Theta_k + R_{k-1}\phi) \\ 1 \end{bmatrix}$$

which leads to the following expressions:

$$P_{nx} = S[L_0\cos(\Theta_0 - \alpha) + \sum_{k=1}^{M} L_k \cos((\Theta_k - \alpha) + R_{k-1}\phi)] - X$$
$$P_{ny} = S[L_0\sin(\Theta_0 - \alpha) + \sum_{k=1}^{M} L_k \sin((\Theta_k - \alpha) + R_{k-1}\phi)] - Y \quad (8)$$

The various normalized link-lengths, L_{nk}, normalized coupling ratios, R_{nk}, and normalized initial configurations, Θ_{nk}, may be extracted by application of the Fourier-based optimal synthesis method to the normalized closed-loop curve. These extracted normalized parameters can now be easily related to the parameters of the SDCSC mechanism that can trace the original curve, as shown in Fig. 4.

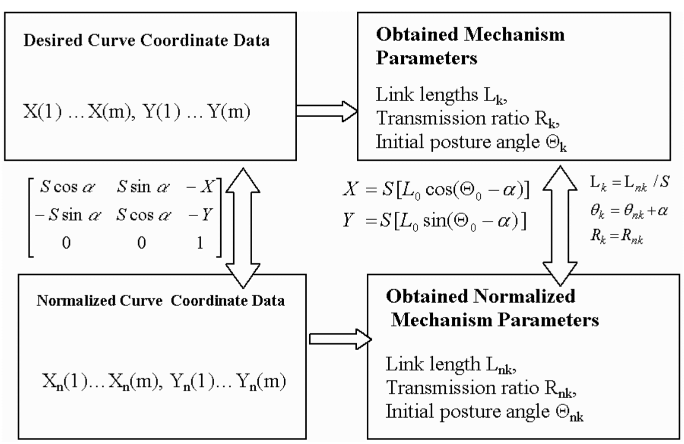


Figure 4: Curve Normalization in Mechanism Synthesis.

Thus, all members of a single family of curves can thus be easily generated by simple adjustment of the principal structural parameters: scaling the link lengths, retaining the same coupling ratio and rotating the entire mechanism by an angle α.

Examples

Verification studies were performed to check the effectiveness and overall utility of our Fourier-based mechanism synthesis method. In Figures 5(a), (c) and (e) the desired normalized task curve takes the form of an equilateral triangle, a square and a hand-drawn curve for which the parameters of the optimal SDCSC mechanism had to be determined. The end-effector paths and some intermediate positions of the resulting optimal mechanisms tracing these paths are depicted in Figures 5(b), (d) and (f). The corresponding parameters of the optimal 3-link SDCSC mechanism are listed in Table 1.

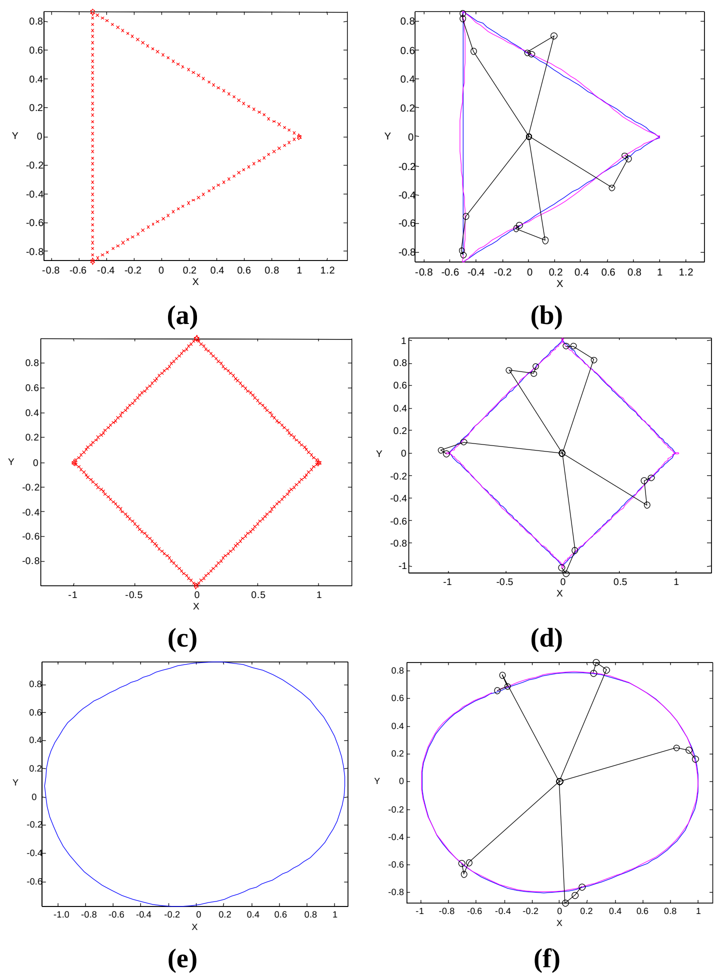


Figure 5: (a,c,e) Examples of Normalized Desired Paths; (b,d,f) End-effector paths of computed optimal SDCSC mechanisms superimposed on the desired paths.

	Normalized Triangle	Normalized Square	Normalized Hand-drawn Curve
L_1	0.728	0.87	0.875
L_2	0.238	0.22	0.091
L_3	0.035	0.064	0.079
R_0	1	1	1
R_1	-2	-3	3

R_2	-5	5	-1
Θ_1	-130.88 ^{o}	71.59 ^{o}	118.25 ^{o}
Θ_2	-98.24 ^{o}	145.23 ^{o}	-64.17 ^{o}
Θ_3	-65.63 ^{o}	177.95 ^{o}	-156.85 ^{o}

Table 1: Manipulator parameters for tracing a variety of normalized curves.

REALIZATION OF A RECONFIGURABLE PROTOTYPE

We now examine some of the issues related to converting the result of the mathematical modeling of the previous section into a physically realizable design. Our overall goal is to create a physical prototype that retains the SDCSC configuration while permitting easy alteration of the principal structural parameters, i.e. the link length, coupling ratio and initial configuration. Hence we discuss some aspects of the physical design realization that permits us to retain these features. Finally, we present the physical prototype that was designed in SolidWorks, refined using Working Model and then fabricated in the machine shop.

Mechanism Parameter Sensitivity Study

The mechanism synthesis described earlier provides the ideal mechanism parameters defining a specific SDCSC which need to be realized exactly in the prototype in order to physically reproduce the planned desired path. However, errors in realizing the exact parameters exist in real world. Hence we investigated the sensitivity of the end-effector path to variations in the structural parameters using a linear Taylor series expansion for the forward kinematics equations of the 3-link SDCSC mechanism. The 11 parameters describing the 3-link SDCSC can be aggregated 3 groups: link lengths (L_0, L_1, L_2, L_3); initial link posture ($\Theta_0, \Theta_1, \Theta_2, \Theta_3$); and coupling ratios ($R_0, R_1, R_2$). E_{L_i}, E_{R_i} and E_{Θ_i} represent the contribution to the error in the path traced by the end-effector due to unit errors in the link lengths, L_i, coupling ratios, R_i, and initial link posture Θ_i and are summarized below.

$$\left\|E_{L_i}\right\| \le 1 \qquad \left\|E_{\Theta_i}\right\| \le L_i \qquad \left\|E_{R_i}\right\| \le L_i \phi_j$$

In terms of the *relative* parameter sensitivity, errors in realizing the exact coupling ratios have the most significant effects on the shape of the generated curve, whereas errors in the exact-link lengths have the least effect, a factor which is taken into account in the physical prototype realization.

Multiple Physical Assembly Modes

Mathematically, the ordering of the terms of an *M*-term trigonometric series does not affect the sum of these terms. However, when considered as an *M*-link SDCSC mechanism, "*M!*" different physical layouts become possible based on the relative ordering of the links. For example, the 6 possible layouts of the same optimal 3-link SDCSC mechanism for tracing a triangle are shown in Table 2 below and depicted in Figure 6. All six configurations trace the same path but have different overall motion characteristic. As a general rule, the link arrangement configuration with decreasing link length is preferred in most cases, because it offers both the ease of construction and greater structural rigidity.

L_1, L_2, L_3	L_1, L_3, L_2
L_2, L_1, L_3	L_2, L_3, L_1
L_3, L_1, L_2	L_3, L_2, L_1

Table 2: Six possible layouts for a 3-link SDCSC mechanism.

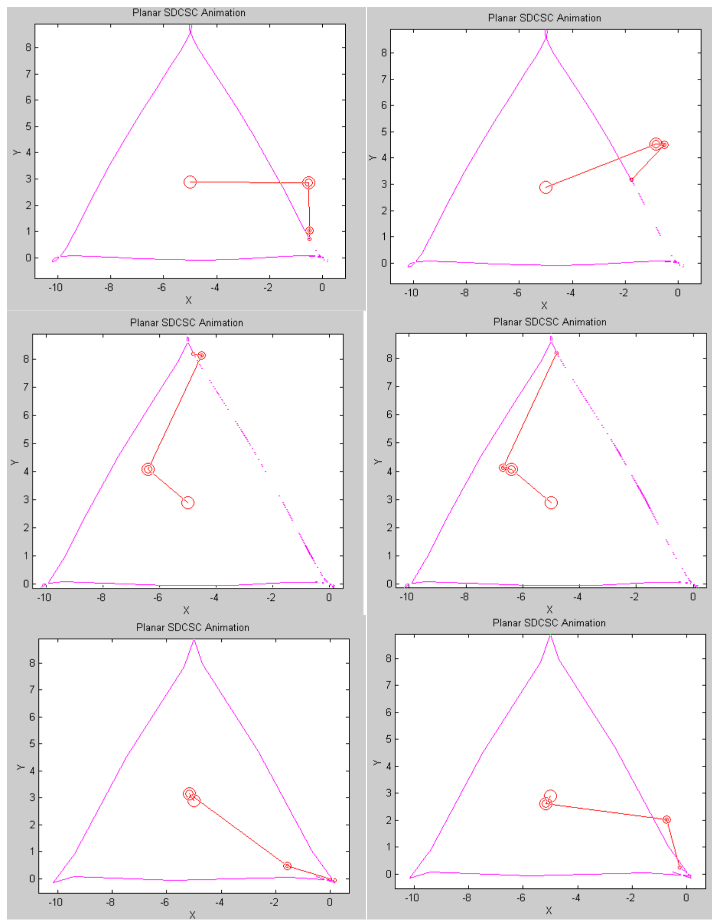


Figure 6: Six possible physical layouts for a 3-link SDCSC mechanism tracing a triangular path.

Physical Design Realization

The physical realization of a reconfigurable prototype, that retained the SDCSC configuration while permitting easy alteration of the principal structural parameters, offered many challenges. Specifically, provision had to be made for the link-lengths to be varied continuously and for the coupling ratios to be varied continuously, over a wide design range.

Variable Coupling Ratios

The characteristic feature of the SDCSC mechanism is the coupling of the joint rotations in hardware. For a single coupling ratio, this may be explicitly realized by coupling the individual joint rotations using cable/pulley drives or gear trains. However this limits the ability to alter the coupling ratio for different tasks as desired in our reconfigurable mechanism.

Hence, we adopt a two-stage process for realizing this realizing the variable coupling ratio as shown in Fig. 7 below. In the first stage, we obtain the three different constant rotational speeds through the use of three speed reducers connected to a common input shaft, driven by a DC motor. Each speed reducer is selected to be a continuously variable transmission (CVT) that provides the desired ratio between the input shaft and output shaft rotation. A screw control permits the user to alter this ratio continuously over the full range. In the second stage, each of the three output rotations is transmitted to the corresponding joint using timing belt and pulley transmissions. Thus the overall system still has only one degree of freedom, the input motor shaft rotation. This two-stage system has the additional benefit of allowing the coupling ratio adjustment system to be mounted at the base, minimizing the inertia of the linkage.

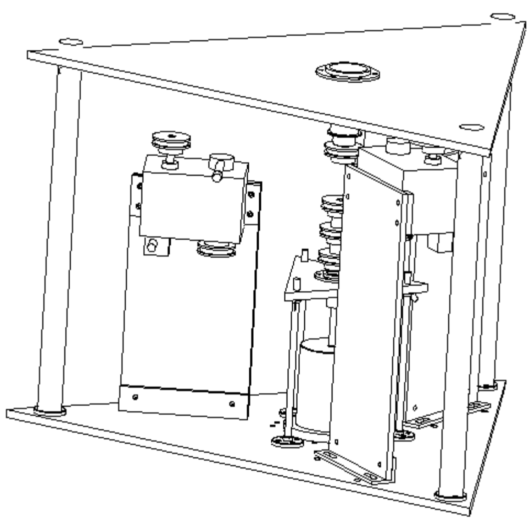


Figure 6: Base design with single central motor and three CVT-based speed reducers.

Variable Link Lengths with Belt and Pulley Transmissions

Another challenge faced in designing this reconfigurable SDCSC prototype is the need to change link lengths continuously, while transmitting the power to the next link using the belt/pulley transmission. In typical cases, any change in link length would alter the center-center distance between the pulleys and prevent the transmission of power.

Hence we employed a design where each link consists of two parts that can move relative to each other, that can be accurately controlled using a lead screw arrangement. The first part, also called the fixed part, supports 3 pulleys (1, 2 and 3) while the adjustable part support the remaining 2 pulleys (pulley 4 and 5) as shown in Figure 7. A single belt runs over all the pulleys as shown in the figure. Pulley 1 is attached to the rotation of the proximal joint while pulley 5 is connected to the distal joint rotation effectively coupling the two. The interesting feature is that regardless the relative motion of the fixed and moving parts (and thus the center distance between input pulleys 1 and output pulley 5), the belt length remains the same as can be seen in Figure 7.

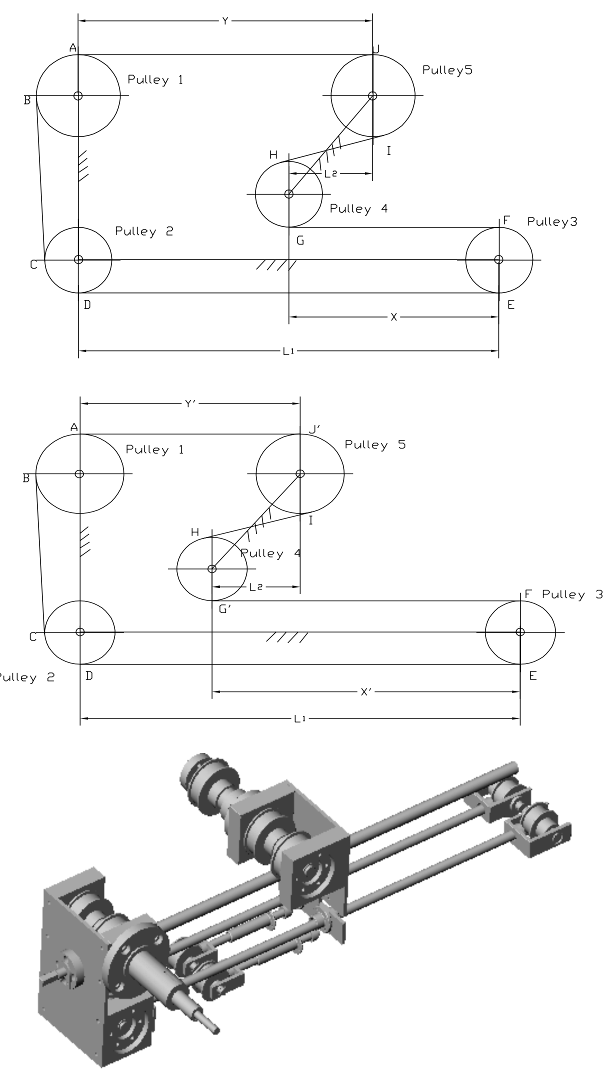
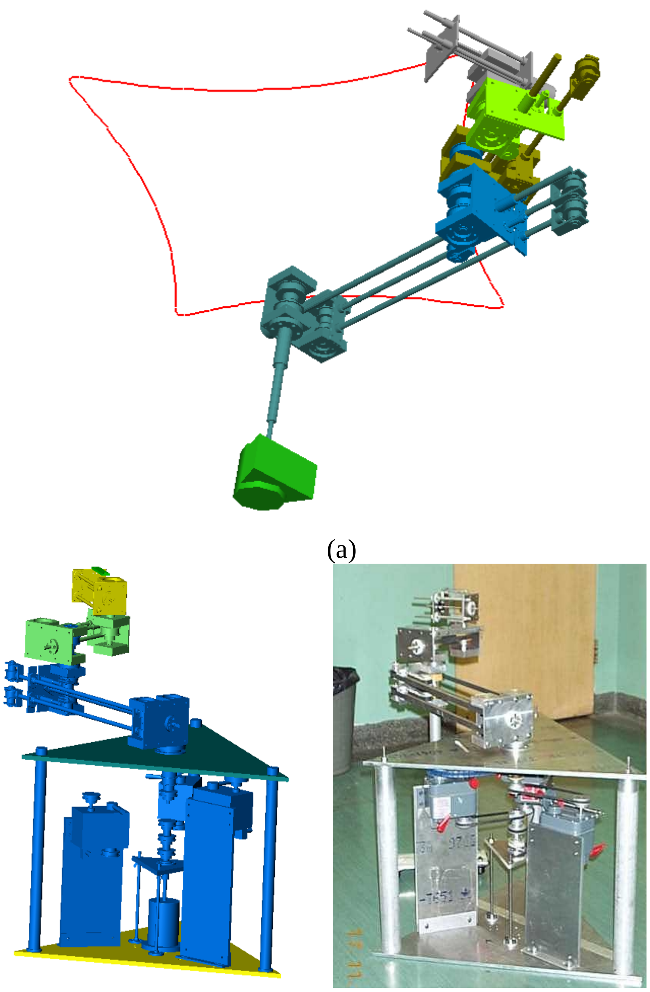


Figure 7: Constant belt length can be maintained despite varying link length (between Pulleys 1 and 5).

CAD Design

The CAD design of the entire system was done using SolidWorks. This package permits ease of parametric part and assembly design of the entire system as well as a number of interfaces for export of the generated model to other analysis and manufacturing system. The design was tested and analyzed in Working Model as shown in Fig. 8(a) which permitted multiple versions of designs can be tested and optimized. Figure 8(b) shows the complete CAD assembly of the linkage and the base used to build the physical prototype shown in Fig. 8(c).



(a) (b) (c)

Figure 8: (a) Working Model simulation (b) CAD model of the reconfigurable 3-link manipulation assistive aid and (c) Fabricated prototype.

DISCUSSION

The overall goal of this research was to investigate the ability to design and prototype a reconfigurable, single degree-of-freedom, articulated, manipulation-assistive aid that is capable of tracing constrained closed-loop end-effector paths in the plane. To this end, we examined the use of tools from mechanism synthesis and analysis, Fourier-based methods, optimization and simulation and then CAE tools to aid the process of design, refinement and ultimately physical prototyping.

A software package was developed to implement the design synthesis method using MATLAB. Special emphasis was placed on the development of a Graphical User Interface to aid the designer in the process of task specification, optimization-based synthesis and subsequent analysis of the result. This method was shown to be useful in designing SDCSC-type manipulators to trace a wide variety of polygonal as well as hand drawn end-effector paths. Further, we investigated methods of classification of the desired planar closed-loop curves into families and determination of the relationship between the members of a single family and the principal structural parameters. Finally, we examined the process of converting the mathematical model into a physical prototype with the ability to reconfigure for new tasks by a controlled variation of alter the principal structural parameters.

Ongoing Work

In ongoing work, we are investigating the addition of actuators to the screw controls of the continuously variable transmissions and the lead screws of telescoping links to enable us to vary the principal structural parameters under computer control. Computer control of the variation of these parameters permits us to actively control the set of constraints (on both trajectories and forces) at the end effector. The resulting system is still passive since the actuation and computer control is only used to alter the structural parameters and not for actuating the joints, making them safe for use in contact with humans.

Further, while the hardware constraints restrict the motion of the end-effector to the constraint surface in the task space, they do not restrict motions along the constraint surface. Hence in our current work, we are also exploring the addition of a motor at the base to not only provide power augmentation but to also stabilize disturbances that occur when performing such constrained motions.

ACKNOWLEDGMENTS

We gratefully acknowledge the support of the Canadian Natural Sciences and Engineering Research Council and the McGill Petro-Canada Young Innovator Award.

REFERENCES

[1] Kota, S. and Erdman, A.G., 1997, "Motion Control in Product Design," *ASME Mechanical Engineering Magazine*, 119(8), pp. 74-77.

[2] Krovi V., 1998, Design and Virtual Prototyping of User-Customized Assistive Devices, *Ph.D. Thesis*, Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA.

[3] Hunt, K.H., 1978, *Kinematic Geometry of Mechanisms,* Clarendon Press, Oxford.

[4] Kazerooni, H., and Guo, G, 1993, "Human Extenders," *ASME Journal of Dynamic Systems, Measurement, and Control*, 115(2), pp. 281-290.

[5] Colgate, J. E., & Brown, J. M., 1994, "Factors Affecting the Z-Width of a Haptic Display," *Proceedings of 1994 International Conference on Robotics and Automation*, pp. 3205-10.

[6] Troccaz, J., and Delnondedieu, Y., 1996, "Semi-active guiding systems in surgery. A two-DOF prototype of the passive arm with dynamic constraints (PADyC)," *Mechatronics,* 6(4), pp. 399-421.

[7] Krebs, H. I., Hogan, N., Aisen, M.L., and Volpe, B.T., 1998, "Robot-Aided Neuro-Rehabilitation," *IEEE Transactions on Rehabilitation Engineering*, 6(1), pp. 75-87.

[8] Li, P., and Horowitz, R., 1999, "Passive Velocity Field Control of Mechanical Manipulators," *IEEE Transactions on Robotics and Automation,* 15(4), pp. 751-63.

[9] Book, W., Charles, R., Davis, H., and Gomes, M., 1996, "The Concept and Implementation of a Passive Trajectory Enhancing Robot," *Proceedings of the ASME Dynamics Systems and Control Division,* DSC-Vol 58.

[10] Goswami, A., 1993, Mechanical computation for passive force control, *Ph.D. Thesis*, Northwestern University, Department of Mechanical Engineering, Evanston, IL.

[11] Wannasuphoprasit, W., Gillespie, R. B., Colgate, J. E., and Peshkin, M. A., 1997, "Cobot Control," *Proceedings of 1997 IEEE International Conference on Robotics and Automation*, vol. 4, pp. 3571 –3576.

[12] Moore, C.A., 1997, "Continuously Variable Transmission for Serial Link Cobot Architectures," *M.Phil. Thesis*, Department of Mechanical Engineering, Northwestern University, Cleveland, OH.

[13] McGovern, J. F., and Sandor, G. N., 1973, "Kinematic Synthesis of Adjustable Mechanisms - Part 1: Function Generation and Part 2: Path Generation," *ASME Journal of Engineering for Industry*, 95(5), pp. 417-429.

[14] Chuenchom T. and Kota S., 1997, "Synthesis of Programmable Mechanisms Using Adjustable Dyads," *ASME Journal of Mechanical Design*, 119(2), pp. 232-237.

[15] Erdman, A. G., 1995, "Computer Aided Mechanism Design - Now and the Future," *ASME Journal of Mechanical Design*, 117(2B), pp. 93-100.

[16] D. A. Ruth and J. M. McCarthy, 1999, "The Design of Spherical 4R Linkages for Four Specified Orientations," *Mechanism and Machine Theory*, 34, pp. 677-694.

[17] Pang Y.W. and Krovi V., 2000, "Kinematic Synthesis of Coupled Serial Chain Mechanisms for Planar Path Following Tasks using Fourier Methods," *Proceedings of the 2000 ASME Design Engineering Technical Conferences*, Baltimore, MD, DETC2000/MECH-14188.

[18] Nie, X., 2001, "Design of Reconfigurable Manipulation Assist Aids by Fourier Methods," *M. Eng. Thesis*, Department of Mechanical Engineering, McGill University, Montreal, Canada.

[19] Wandling G., Abir S., and Flugrad D. 2000, "Application of Spatial and Fourier Transforms to the Synthesis of Path Generation Mechanisms," *Proceedings of the 2000 ASME Design Engineering Technical Conferences*, Baltimore, MD, DETC2000/MECH-14190.