A Compliant Five-Bar, 2-Degree-of-Freedom Device with Coil-driven Haptic Control

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Background / Motivation

Our team has designed and built a compliant 5-bar haptic device with two degrees of freedom. The device can be manufactured in a shop by undergraduate students. It serves as a test bed for experimental control design and as a valuable tool for hands-on teaching of haptic controls. It is also significant in demonstrating the potential to use compliant joints in other haptic devices.

Our haptic device provides a force-feedback interface with a human user at a single point in a plane. The human can move this “end-effector” anywhere within the 2-D workspace, while the device monitors the movement and can apply any force of arbitrary magnitude and direction to the user, through the same end-effector. It is then possible to create a virtual environment. Any two-dimensional virtual environment can be created, complete with interactive virtual springs, sprung masses, walls, gratings, viscous fluids, negative stiffness, and more.

This work explores the marriage of compliant mechanisms and haptic controls, looking at how each technology benefits each other and also at unique benefits gained only through their combination. Some of the problems with friction and controls are resolved and new methods of handling control instabilities are discovered.

WHAT’S NEW?

While we begin with a 5-bar pantograph linkage familiar to other 2-D haptic devices, the playing field is changed with the integration of flexure joints. The compliant joints add many benefits over conventional pin joints. However, there is now the presence of joint moments, which may appear to be a disadvantage at first but lead to some interesting aspects in haptics control. The flexure joint offered another challenge in the re-engineering of the typical device assembly.

Students with different backgrounds came together to achieve integration of design on many levels, including:

- Kinematics
- Mechanics
- Compliant Mechanisms
- Heat Transfer
- Controls
- Eddy Current Damping
- Force Feedback
- Motors
- Ease of Manufacture

APPLICATIONS

Haptic devices can be found in many applications, including tele-robotics, rehabilitation, gaming, and skill training. Another area we are specifically interested in is the education of dynamics and system theory. While figures, formulas, and analogies help to some extent in teaching these subjects, it is believed that direct interaction with the forces being studied increases the ability to understand and retain concepts.
Sprung System
The creation of a “sprung” haptic device is also desirable for those applications that favor a “home” position, i.e. the resting position of the mechanism. These applications include gaming and rate-control operations performed with a joystick.

The sprung system does bring some problems to the virtual environment in some applications. Instabilities can arise in some cases, for example when trying to create virtual home-position at locations other than natural home position. We’ve discovered this problem can be solved by adding eddy-current damping to our device, making possible tunable haptic systems with balanced stiffness and damping.
**Application Awareness**

Our design decisions also reflect an application awareness of both low-end and high-end devices. Low-end devices, such as those used in gaming and education, are currently cost-inhibitive due to expensive precision components such as bearings. They benefit from our low-cost, zero-backlash joint design. In high-end applications, accounting for the coulomb friction forces is troublesome for control. Our design eliminates these forces and replaces them with easily-modeled spring forces.

**MAIN STORY: 5-Bar Mechanism with Compliant Joints**

**BENEFITS**

In addition to simplifying manufacture, part count, and lowering cost, compliant joints provide another important benefit in a haptic device. The friction from the conventional joints has now been replaced with the torsional spring forces. Spring forces are much easier to model than friction (non-conservative, nonlinear), and thus make it much easier to implement a controller.

**PROBLEMS**

Compliant joints do not have the nearly infinite out-of-plane stiffness of conventional joints and must be designed to have high off-axis stiffnesses. A finite range of motion must also be dealt with to allow for a sufficiently large workspace of the end-effector. As mentioned, there is now a home-position for the device, which may or may not be a desired aspect. Finally, compliant joints can take up much more space than pin joints, especially in the out-of-plane direction, which must be kept to a reasonable minimum.

**DESIGN**

**Compliant Joints**

Compliant “open-cross” revolute joints provide low cost, friction-free, zero backlash connections between links. The design task is to minimize their torsional stiffness while keeping minimal size constraints and off-axis stiffness.

![Figure 2: Cross-Section of “Open Cross” Revolute Joint Beam](image)

The “open-cross” revolute joint used (See Figure 2) was developed by two of the authors, a modification of a design developed by one of the authors and his advisor. This design offers a greater range of motion and high off-axis stiffnesses than many other flexure joints. More importantly, it is a kinematically well-behaved flexure, allowing little to
none drift of its center of rotation (i.e. “parasitic” motion). The formulas are found in Table 1.

**Table 1: Analytic Stiffness Table**

<table>
<thead>
<tr>
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<th>Formula</th>
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<tbody>
<tr>
<td>Torsional [N-mm/rad]</td>
<td>$24 \frac{EI_1}{L^3} + 8 \frac{GK}{L}$</td>
</tr>
<tr>
<td>Bending [N/mm]</td>
<td>$48 \frac{E(I_1+I_2)}{L^3}$</td>
</tr>
<tr>
<td>Axial [N/mm]</td>
<td>$2 \frac{AE}{L}$</td>
</tr>
<tr>
<td>Range Of Motion [±rad]</td>
<td>$0.577 \frac{\sigma_{ys}L^2}{\sqrt{[2.25(EQ)^2(w+g)^2 + 3(KGL)^2]}}$</td>
</tr>
</tbody>
</table>

**Note:**
- $I_1 = \frac{1}{12}wt^3$; $I_2 = \frac{1}{12}tw^3$; $A = 4wt$;
- $K = \frac{wt^3}{16} [16/3 - 3.36 t/w (1-t^4/(12w^4))]; \quad Q = \frac{w_t^2}{3w+1.8t}$
- $E$~Young’s Modulus; $G$~Shear Modulus; $\sigma_{ys}$~Yield Strength

**Figure 3: Cut-section view of an “Open-Cross” Compliant Joint**

**5-Bar Linkage with Torsion Springs**

The linkage is a basic 5-bar pantograph design often used for 2-D haptics. A previous design created by team members with conventional pin joints is shown in Figure 4. The pentagram configuration allows for a nearly diamond shaped workspace, shown in Figure 1.

Fabrication is geared to the capabilities of students in our undergraduate design courses. The 2 degrees of freedom of our mechanism are controlled by 2 hand-assembled high torque motors, also visible in Figure 4. The motors are essentially hand-made voice-coil motors, consisting of a coil of motor wire sandwiched between two large magnets. Note that each input link actually has two voice coils (for a total of four), doubling the output power.
The motor housing has been designed to maximize cooling of the motor coils. Overheating coils initially melted the plastic components, prompting the inclusion of heat sink metals and a cooling fan. The inclusion of the moving metals within the magnetic field creates an eddy-current effect, to be further discussed in the controls section.
Much redesign went into the link and motor housing assembly. CAD modeling was used to create the required link clearances, room for coils, room for heat sinks, and room for the cooling fan. The links were made modular for easy assembly and replacement. Thus far our links have been made from ABS plastic via a rapid-prototyping machine. Future versions of the device may contain plastic injection molded parts.
Sensors and Positioning
Position sensing is achieved via optical encoders. Novel use is made of linear encoder strips to measure the angular rotation of the two input links. From these two angular positions, the position of the end effector is calculated, requiring only the geometry and kinematics of the linkage. The sensors and motors are interfaced to software controllers on a computer to achieve closed-loop control.

ANALYSIS
Compliant Joints
ADAMS software was used to observe the geometric nonlinearities arising in the compliant joints. The small-displacement stiffness values match those from our above equation, and ADAMS provides the function for the stiffening effect of large rotations. This function is easily substituted for single stiffness values initially used in our Matlab code described next.
**Mechanism Analysis**

Motor torque requirements, workspace size, and the torque-displacement relationships for control were calculated with Matlab models. The kinematic equations relating input link angles ($\theta_1$, $\theta_2$) to end effector position (x, y) were found with basic trigonometry. The inverse kinematic relationships were also found, relating the deflection of each of the 5 joints to the x-y position of the end effector. We therefore know the maximum rotation of any of the 5 joints for all end-effector positions and can plot this as seen in Figure 7. Given the calculated range of motion for the joints we are using, this plot then indicates the workspace of the 5-bar mechanism as limited by joint stress.

**Figure 7. End Effector workspace as determined by maximum allowable joint rotations (before yielding)**

Calculation of force relationships requires inclusion of the joint torques, depicted in Figure 8. Treating the compliant joints as simple torsion springs with stiffness as calculated above, the kinematic and static analyses are combined to produce the 2-D mapping of motor torque shown in Figure 9. Figure 9 actually shows the greater of the two motor torques required to move the end-effector into any particular x-y position.
Thus, while Figure 7 shows the workspace as limited by joint stresses, Figure 9 shows the workspace as limited by available motor torque. Together, these two figures are a valuable tool in making sure all constraints are met and determining the true design space.

Note that in calculating the values for Figure 9, there is assumed to be no force output at the end effector. The actual model used in the real-time controller will include these output forces in order to generate virtual environments. Also note that the actual workspace is somewhat smaller than that depicted in Figure 9; by not going all the way to the edges, we leave some remaining torque available to provide force-feedback on the user.

Figure 8. Depiction of Torsion Spring Forces to be included in static analysis of compliant 5-bar
CONTROLS

The replacement of bearing friction forces with torsional spring forces has dramatically simplified and improved control. Control is accomplished by connecting our motors and sensors to a Windows PC via a commercial interface provided by Opal-RT. The control programs are written in Simulink with a toolbox provided by Opal-RT.

Figure 9: End Effector workspace as determined by available motor torque
Spring Elimination
Our first task was to use the controls to virtually eliminate the spring forces. Once this was accomplished, a user could move the end effector about without feeling the spring forces. This elimination of a home-position creates a blank design space in which to create virtual environments.

The actual spring-canceling controller design can be accomplished in two ways. The combined kinematic-stiffness analysis from above can be used to directly compensate for spring forces. Alternatively, we can set the device to “auto-calibrate”. By moving the end-effector throughout its work space we create a 2-D mapping function of the required torques. This mapping function replaces our analyses. We are currently using the device to determine effectiveness of each approach.

Hysteretic Damping
The discovery of the effect of hysteretic damping from eddy-current damping has encouraged our further research of combined compliance and haptics. As mentioned, the device suffers from instabilities in the creation of some virtual environments. However, the eddy-current damping smooths out these instabilities. That we can control the system stiffness and the amount of hysteretic damping allows for ideal tunability of the system.

EDUCATION
The compliant-haptic device has already been used in undergrad design classes. Students have implemented it both as a 2-D robot and a 2-D haptic test bed. They were also able to perform some of the auto-calibration techniques described above to virtually eliminate the mechanical stiffness. The students have thus far gone through 5 of our prototype devices – they are providing us with a very rigorous testing environment and supplying valuable feedback for us to implement in the next generation of devices.