Lessons from the Design and Testing of a Novel Spring Powered Passive Robot Joint

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***Abstract*— The design, assembly, and testing of a new torsional spring joint for use in underactuated robots is presented. The joint can use an array of spring sizes and is able to adjust the spring offset and preload independently. This work outlines the design process with details on the troubles faced and lessons learned from multiple redesigns.**

I. INTRODUCTION

The design of new mechanical parts and assemblies is an integral part of robotics research. Even when an engineer's research is mainly theoretical, it is typically expected that the theory will be tested in an experimental setup, often requiring the design of specialized pieces and devices, either for testing by themselves or inclusion in a larger robotic setup. While there exist many design and testing methodologies for mechanical and mechatronic parts and assemblies, when seeking to create a one-off prototype there is normally not enough time for these long processes. The engineer must try to quickly design, build and test an assembly, being efficient and using only as much time as is necessary to ensure the design criteria is achieved. And this all must be done without running into dead ends or overly difficult problems during any stage of the build-up.

This work presents the design and build process of a torsional spring joint with a special emphasis on the problems encountered and the lessons learned. A short background sets the stage for a discussion of the design goals and the resulting initial design. Then the assembly and testing are discussed with a presentation of the problems, attempted solutions and final torsion joint layout. Lastly a discussion presents the key lessons learned from this experimental work and how they can contribute to prototype design in the future.

A. Background

While working on a stable system inversion method for the control of underactuated robots, a technique first investigated by [1] and expanded by [2], there arose a need for an underactuated robot, for testing of the method proposed in [3]. The motivation behind designing and building an underactuated robot was twofold, first it would provide a experimental platform to test the theoretical system inversion method mentioned above, and second, it would give insight into the general capabilities and usefulness of such a robot.

The robot is required to perform cyclic(repeating) tasks and is made up of two linkages in a planar arrangement. There is an actuator at the first joint and the torsional spring mechanism at the second joint, see Figure 1 for a simplified model of the robot. The actuator and passive joint placement ensures that the robot is underactuated but not completely uncontrollable, as backed up by the general serial-link robot analysis done in [4]. There are many reliable sources to use when working with springs and mechanical design, though [5] was consulted most often for this project.

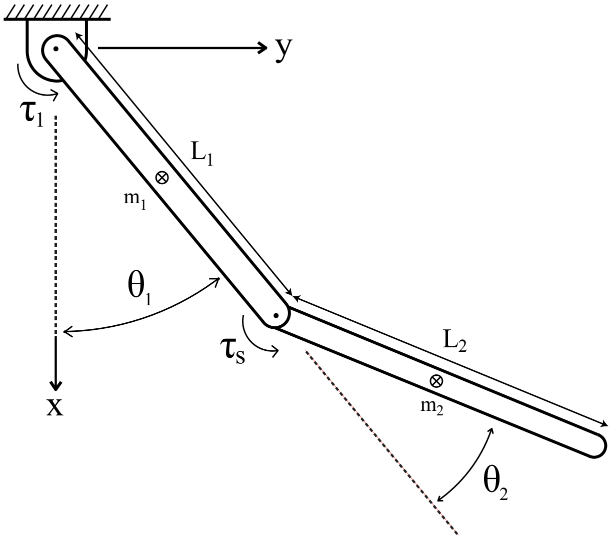

Fig. 1. 2DOF planar robot with torsional spring joint

The use of torsion springs to provide a passive torque, that depends on the position and arrangement of the spring, is a very old idea and most easily seen in the common clothespin, yet its use in robotics has been limited. An early study of torsional springs within the dynamics of the a generalized robot framework can be seen in [6]. Other closely related work focuses on using springs in conjunction with actuators, normally classified as passive-compliant or variable stiffness actuators. A useful survey of various passive-compliant actuators, where the springs basic properties are used without

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adjustment, is seen in [7]. Some variable stiffness actuators use actively adjusted springs, as seen in [8], showing an additional connection to biomechanical design.

The design presented here is unique in two ways; first it is very versatile, capable of using many different size springs, second, it is highly adjustable, allowing the offset and preload to be set independently. Though experimental, this joint allows for greater investigation into the capabilities and usefulness of torsional springs within the serial-link robot framework.

II. DESIGN

The design of the torsional joint was performed using the traditional tools and methods of the mechanical engineer. After developing a few possible ideas that led to sketches and drawings, the most promising one was built up in a computer aided drafting (CAD) program (Autodesk Inventor) with the creation and virtual assembly of the parts. The completed initial design of the prototype led to the manufacturing and assembling of the parts. The build, test, and redesign cycle was run through twice with the final prototype showing reliable performance in all important areas of the design.

A. Design Goals

Adapting the basic spring principles and capabilities for use in a torsional spring driven joint started with a review of what was needed from the joint. The design goals were created by reviewing the needs of the overall robot as well as the materials and space available. The goals are built around keeping the design simple and are listed below:

1) Use a single torsion spring
2) Offset and preload angles must be adjustable
3) Spring body width must be adjustable
4) Only use the spring in compression
5) Allow an optical encoder to read the angular position

The experimental nature of the joint drove the first and second goals, to allow for adjustment of the spring position and initial torque. The use of different springs prompted the third goal. The fourth design goal was created after investigating the proper use of torsional springs, they are not made to be used repetitively in both tension and compression. Most manufactures recommend only using them in compression. The last goal is due to the experimental nature of the mechanism and enables the angular position feedback from the joint to be recorded, allowing further study and evaluation of the robots motion in post processing.

B. Implementation

The simplest and most direct design uses only one spring and two pairs of hook and flange subassemblies. Each hook plate is attached to a flange that is stacked with another flange with both secured to the robot linkage. There are two flanges per link, one set has long flange arms and the other short flange arms. This hook hand-off design, with the two different flange arm lengths, ensures that the torsion spring is only used in compression, no matter if the linkage moves in the positive or negative radial direction.

The flanges can be rotated independently, along the chamfered slots, when the screws are loosened as seen in Figure 2. The flange slots allow both the preload and offset of the spring to be adjusted within a limited range of positions. The range of motion and possible adjustment is outlined in Table I while the setting ranges of the offset and preload are shown in more detail in Figure 3. The graph helps show that as the offset is adjusted the available offset range also changes, this is due to the limits of the mechanical setup.

The spring sits around the joint axle with the second link mounted to the axle using a mini-bush clamp, this allows the linkage to be placed higher or lower on the axle depending on the size of spring used. The axle is secured to the first joint with a single ball bearing.

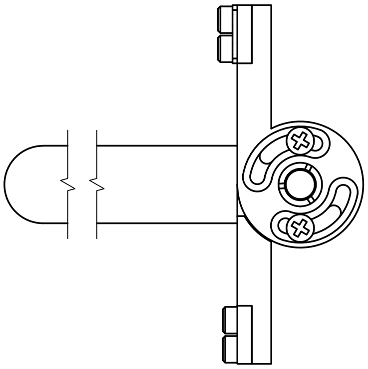


Fig. 2. Linkage 2 flange attachments

The last design goal, allowing an encoder to read the angular position, was fulfilled by creating a joint axle with a small protruding extension at the bottom. An encoder could then be mounted on the underside joint, specifically on the end cap spacer, with the optical wheel mounted at the end of the axle.

TABLE I

TORSIONAL SPRING JOINT PROPERTIES

Parameter	Stiffness	Offset	Preload	Link 2 Motion
Variable	k	θ_f	θ_p	θ_2
Range	$(0.02, .01)$	± 50	$(-20, +80)$	$(-175, +270)$
Units	Nm/rad	$degree$	$degree$	$degree$

The overall design can be seen in Figure 4 with its related parts list in Figure 5. All of the design goals were achieved in the general design layout, though only by building the torsional joint and testing it could the mechanism be deemed successful.

III. ASSEMBLY AND TESTING

The prototype went through a cycle of assembly, testing, and redesign, twice before the arriving at the final setup. Therefor are three designs, denoted alpha(original), beta, and final. The difficulties encountered at each stage are discussed leading to the proposed solutions and redesign.

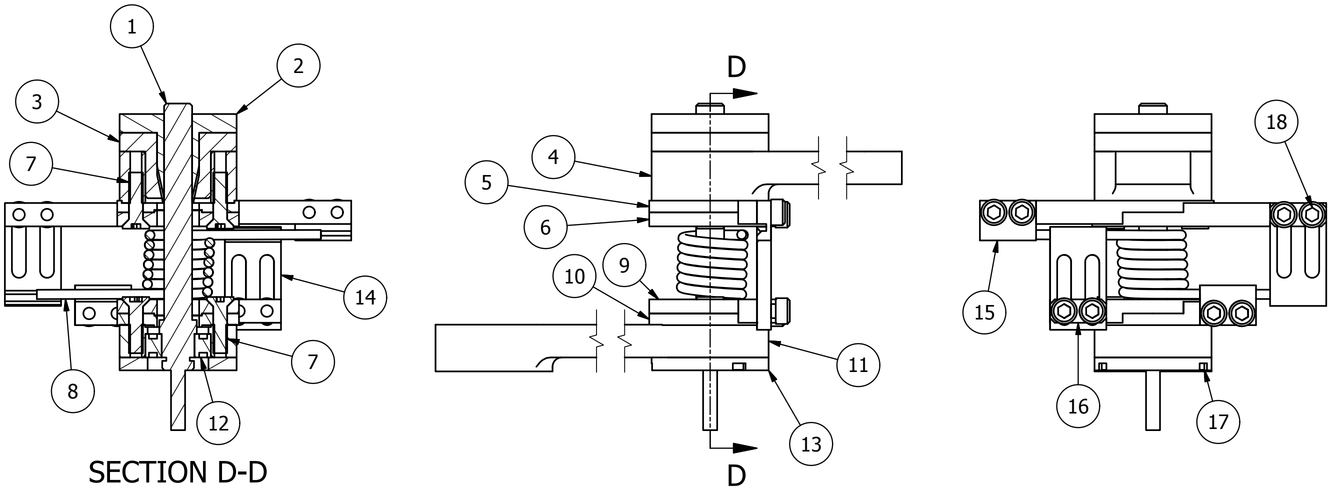


Fig. 4. Overall design of the torsional joint, optical encoder to be mounted at the joint underside, to linkage 1

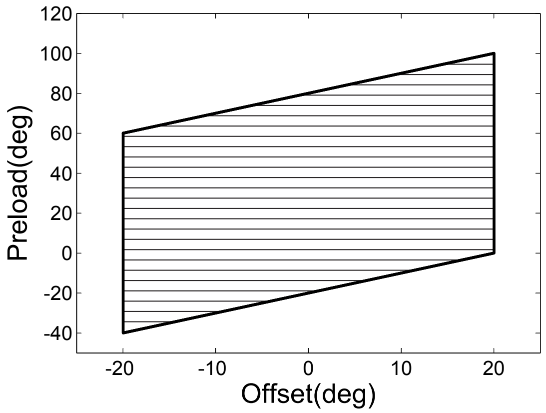


Fig. 3. Range of Torsion joint settings

PARTS LIST		
ITEM	QTY	PART NUMBER
1	1	Joint 2 Axle
2	1	Mini-Bush Inner
3	1	Mini-Bush Outer
4	1	Linkage 2
5	1	Upper Flange2
6	1	Upper Flange1
7	4	M3x10 CSK
8	1	Torsion Spring
9	1	Lower Flange1
10	1	Lower Flange2
11	1	Linkage 1
12	1	Ball Bearing
13	1	End Cap Spacer
14	2	Long Hook
15	2	Short Hook
16	2	Washer Plate
17	3	M2x6
18	8	M3x6

Fig. 5. Torsion joint parts list

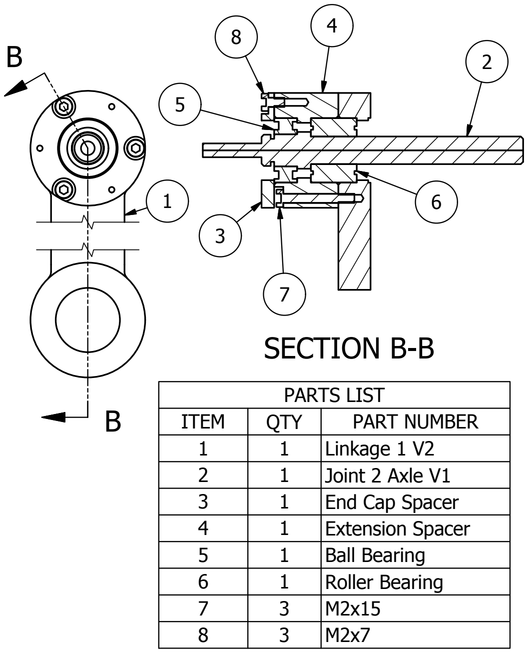
A. *Alpha results*

The parts for the torsional spring joint were sent out for manufacture at a local machine shop while the mini-bush, springs, and hardware(bolts) were procured from local suppliers. Upon receiving the parts and assembling the joint a major problem was observed; the bore in linkage 1, to house the ball bearing was cut 1mm to short, causing the bearing to protrude from the housing. This was discouraging but before sending the part back to be finished properly, the rest of the assembly was constructed to check for other problems.

Additional investigation proceeded despite the improper fit of the bearing and another major problem was found. The ball bearing tolerances were far too loose and allowed the axle to wobble from side to side. This caused the hook hand-off to sometimes miss and more importantly the optical encoder could not function reliably under such wide tolerances. After considering this major problem of axle wobble, it was thought that by adding a roller bearing to the axle the problem could be fixed with the addition of only one new machined part, an extension spacer. All the original parts could still be used. This new design compensated for the previous machining error, a drawing of the new bearing package can be seen in Figure 6. The tolerance limit of the encoder was closely consulted but due to the lack of precise bearing tolerances from the manufacturer the redesign had to rely on the best estimates of the engineer.

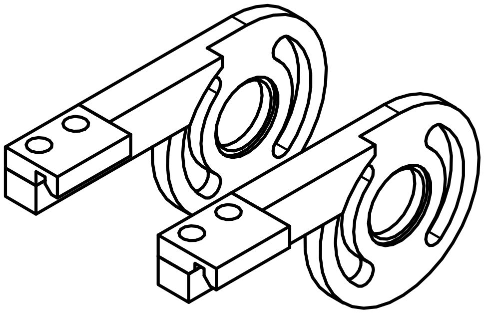
Lastly, as part of the hook hand-off difficulties, the short hook trough (where the spring sits on the hook) was found to be too close to the flange, making it difficult for the long hook plate to grab the spring leg at the hand-off. The new hooks would be needed to allow for easy transition, a comparison of the old and new hooks is seen in Figure 7.

The hook plates lacked specific angular markings, so preload and offset angles had to be estimated. In order to change out the torsion spring or adjust the preload or offset the second linkage had to be removed from its axle. This was not difficult due to the locking mini-bushings used, though



PARTS LIST		
ITEM	QTY	PART NUMBER
1	1	Linkage 1 V2
2	1	Joint 2 Axle V1
3	1	End Cap Spacer
4	1	Extension Spacer
5	1	Ball Bearing
6	1	Roller Bearing
7	3	M2x15
8	3	M2x7

Fig. 6. Second torsion joint design (Beta)



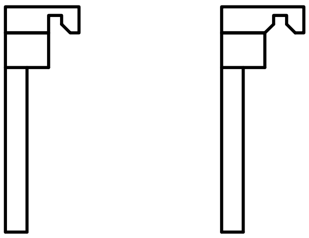
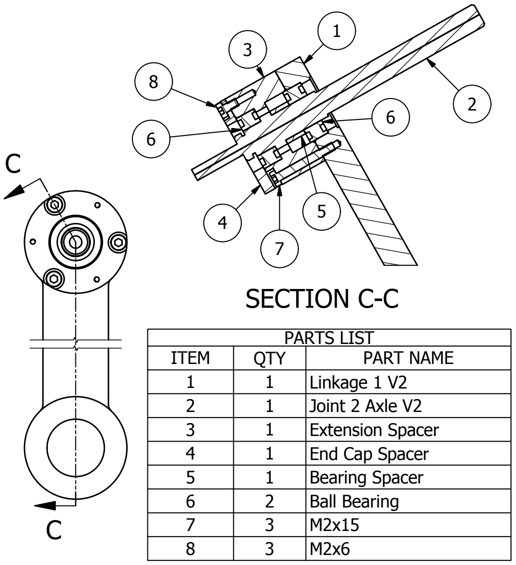


Fig. 7. Old hook (left) with new hook (right)



PARTS LIST		
ITEM	QTY	PART NAME
1	1	Linkage 1 V2
2	1	Joint 2 Axle V2
3	1	Extension Spacer
4	1	End Cap Spacer
5	1	Bearing Spacer
6	2	Ball Bearing
7	3	M2x15
8	3	M2x6

Fig. 8. Final bearing package

it made adjustments a tedious affair.

B. Beta results

With an additional roller bearing, a new short hook, and the extension spacer the second assembly proved to still contain difficulties. The new short hook allowed the hook hand-off to proceed smoothly despite the fact that the joint axle wobble was still too great. The roller bearing did reduce the axial play (in terms of the wobbling) but not enough to allow for reliable readings from the optical encoder mounted on the bottom. It was at this point decided that an adjustable bearing package would be the best solution, then the tolerances of the ball bearings would not be an issue. The final bearing setup is seen in Figure 8.

The final design required a new joint axle that was slightly longer as well as a bearing spacer for the axle. An additional ball bearing was also needed. The measurements sent to the machine shop, regarding the bearing package, were kept rough such that upon assembly the engineer could adjust the fit of the bearing package to allow an appropriate amount of play. If the bearings package is too tight and the axle won't turn, the bearing spacer can be ground down, while if the package is too loose, the machined surface of the extension spacer (which sits against linkage 1) can be ground down. This is a common method for tuning the bearing clearances of large gearboxes.

C. Final results

The final build-up of the torsional joint can be seen in Figure 9. The tuning of the bearing package was done by hand; by using a hand file and a lathe the extension spacer was ground down progressively, bringing the outer races of the bearings closer together until the axle wobble was eliminated, but it could still freely turn.

The final design was completely successful in achieving all of the design goals. The optical encoder returned a reliable signal while the adjustability of the joint allowed for the use of different springs and numerous different offset and preload setups.

IV. DISCUSSION

The design, assembly and testing of the torsional joint was completed as a prototype, for use in testing a theoretical control methodology and some important lessons can be learned from the process. The failures in design and the route taken in redesigns reveals some beneficial as well as detrimental decisions. These will each be discussed as they relate to either the design of the mechanism or the testing of the assembled parts.

A. *Design Lessons*

Lesson 1: Bring all the design constraints together, explicitly listing how they need to be achieved.

The design goals of a mechatronic system typically involve requirements from the mechanical side, such as bearings, fits and hardware, as well as from electrical parts, such as encoders, motors and other interface pieces. If details are left out, they will often show up as trouble during testing. The design goals in the example were clear when the mechanism was first drawn up, the needs of the torsional spring adjustments were straightforward to implement, but the optical encoder requirements were not explicitly checked in the initial design. This lack of detail in the design goal contributed to the problems found in the first design, leading the the first redesign.

Lesson 2: The simplest solution is not always the best, choose the redesign solution that solves the problem most completely.

When redesigning a part or assembly, the simplest and most minimal design is often the most attractive but when considering the complexity of the possible solutions, go with the one most likely to solve the problem, even if it is more complex. The first redesign of the bearing setup only required one more machined part and one additional bearing, plus it allowed the imperfection of the bearing bore in linkage 1 to be left alone. It was thought to be the most economical, yet there was little to no guarantee that it would solve the axle wobble problem. The adjustable bearing package was slightly more complex but should have been used in the first redesign.

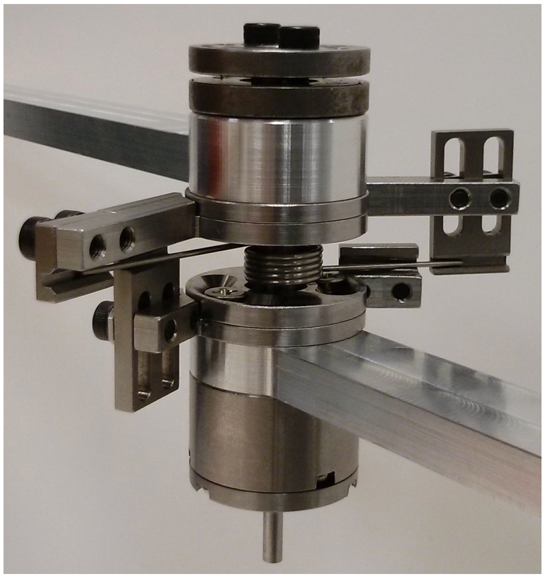


Fig. 9. Final torsional joint setup (without encoder)

Lesson 3: Familiarity with standard engineering solutions that are related to the current design is highly beneficial.

The design of a prototype lends itself to quick thinking and the use of engineering solutions that “may” work or “should” work. Though time is often of the essence and there is not time for an in depth analysis of the parts to ascertain if the part or assembly will meet the design goals exactly it is critical that the engineer have a general understanding of standard industry and engineering practices. Spending time to become familiar with the traditional solutions, relating to the particular parts or assemblies under design, can save time and energy later in the process. This can be readily seen in the example when considering the bearing setup for the joint axle. The first design turned out to be inadequate and only a half measure. Instead, the industry standard for bearing packages which need tight tolerances should have been used right away.

B. *Testing Lessions*

Lesson 4: Test and investigate all aspects of a mechanisms design, as able, before disassembly and redesign.

When working with the design, assembly and testing of prototype, it is important not to get caught up with a single problem such that it distracts from overall testing. This is seen with regards to the machining mistake on the first linkage, where the bearing bore was to short. Instead of immediately sending the part back for correction and having to wait before testing the overall mechanism, the engineer assembled the rest of the parts to examine the part interfaces, the hook hand-off. This additional testing revealed problems that were much more critical than the bore mistake. By testing and examining the assembly as much as possible before trying to fix the small mistake, time was saved and the redesign could include the altered dimensions.

Lesson 5: Implement low risk redesigns early.

Lastly, when working with and testing an assembly of parts that requires a redesign, take time to step back and examine the assembly as a whole, looking for small problems that can be improved with a low risk of affecting the overall working of the mechanism. Including these improvements in a first redesign can save time in later testing. An example of this is seen in the short hook redesign. Though the wobble of the joint axle, when supported by one ball bearing, contributed to an unreliable hook hand-off the engineer was able to identify a second problem area around the short hook. The hook trough was too close to the flange, in order for a successful spring leg hand-off the long hook was required to pass extremely close to the short hook flange. The hook was redesigned to allow for more space between the moving parts. This contributed to a smoother working hook hand-off of the spring, outside of the troubles with the bearings.

V. CONCLUSIONS

When designing, building and testing a prototype mechanism for robotics research there are often difficulties. The short time schedule forces an engineer to make certain assumptions and estimations, which can lead to trouble in the assembly and testing phase. This paper presented the experience of one researcher in designing, building and testing a torsional spring joint prototype. The process faced a few problems but through two redesigns the failures were solved, producing a successful mechanism that met all the required design goals. The lessons learned from this process were discussed in detail and connected to specific examples in the design and testing of the torsional spring joint.

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