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Design of a Spherical Robot Arm with the Spiral Zipper Prismatic Joint

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***Abstract*— A novel prismatic joint called a Spiral Zipper is used to create a 3DOF robot arm in a spherical robot configuration. The Spiral Zipper can be very compact as it has a large extension to compression ratio. An initial prototype has shown a ratio of over 14:1. The Spiral Zipper is very strong in compression, but maybe loose under tension and moments. A tether based system ensures the prismatic joint is always in compression while enabling spherical coordinate positioning with a long reach, high force, low mass design. While having typically an order magnitude higher strength and lower weight ratio for a given reach compared to standard industrial robot arms, the arm is slower and was not designed for high precision. These characteristics may be applicable for mounting on mobile robots or flying vehicles. This paper introduces the design and testing of several prototypes.**

I. Introduction

Robot arms have been used in industry for many decades. More recently researchers have been exploring the use of robot arms mounted on mobile bases [1] and even flying vehicles [2]. One major difference over those mounted on fixed bases is that the mass of the arm is much more important especially if the arm has a long reach which can lead to tip-over conditions for mobile platforms.

Robot arm systems can be classified by many different metrics, but two important ones are the working load and volume of reachable workspace. While an arm capable of full dextrous workspace requires six degrees of freedom (DOF), reachable workspace considers three translation DOF without orientation. Common configurations for these three DOF include a serial arrangement of prismatic (P) and revolute (R) joints such as: articulated (RRR), cartesian or gantry (PPP), cylindrical (PPR), spherical also called polar (RRP) and SCARA (RRP) where the two revolute joints are parallel to each other [3].

One advantage of spherical configurations over others is that collision avoidance and reachability concerns are easier. The standard human-like articulated arm often has difficulty in cluttered environments because the links and elbow sweep out a volume colliding with the environment even when the path of the end-effector or carried object does not. The standard solution is to add more DOF so the elbow can be maneuvered into places that are obstacle-free along with the carried object. A simple approach for path planning with hyper-redundant snake-like arms is to approximate the body-follows-head paths in which the swept volume is only that of the carried object [4]. With line of sight, the shortest body-follows-head path would be a straight line and requires only one DOF. A guaranteed collision-free path from one position to another then has three motions: a retraction, a reorienting, and an extension - ideal for a spherical configuration.

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For robots doing human-like tasks it is useful to see how humans perform. The vast majority of objects manipulated by humans are reachable by a straight line, even in a cluttered environment. If you can see the object, there is line-of-sight and therefore a straight line path to that object. It is rare for humans to grasp objects that they cannot see. Examples of specialized exceptions include reaching into pockets or reaching blindly around furniture or under a bed.

The goal characteristics of this system are long reach, high-strength to weight ratio, low profile and low cost. Precision and speed are not a priority. The core of this system is a novel prismatic joint called the *Spiral Zipper* [5]. Important metrics that characterize a prismatic joint include, the extension ratio (length fully extended to length fully collapsed), the strength of the formed tube (ability to withstand forces) and the mass. Often the latter two are coupled so a strength to weight ratio is often used to characterize both.

This paper will discuss the design and testing of a new robot arm system using the Spiral Zipper in conjunction with winches and cables shown in Figure 1 able to achieve a high extension ratio as well as forming a high strength to weight ratio column to support large loads in a spherical manipulator system.

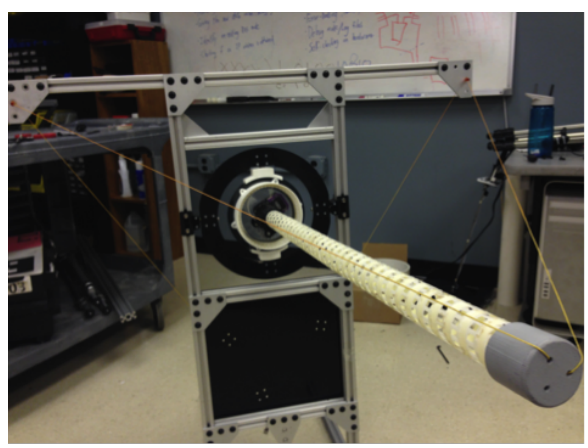

Fig. 1. A 17mm diameter Spiral Zipper mechanism is mounted on a gimbal with 2 winch/cables in a spherical robot arm configuration.

A. Related Work

There are three forms of related work: spherical robots, cable-based systems and expanding tube prismatic joints.

Spherical robot arm systems include the Stanford arm, and the first Unimate from the 1960's [3]. The prismatic joint used in these systems are rack-and-pinion style or leadscrew mechanisms where a long rigid link is translated to extend or retract the end effector. Even when not extended forward, the unused portion of the link is extended backward requiring large clearance. These system precision requirements often lead to stiff links which are higher cost and/or heavy. The large clearance, high cost and weight of these systems may be the reason that spherical robot arms are not as popular as articulated systems. With the growing popularity of lightweight human-safe industrial arms such as Baxter and Universal Robots UR3 there has been a trend towards lower precision, lower inertia, lower cost systems capable of working in the presence of humans.

Winch and cable actuation is ideal when the goals for a robot arm are long reach, light weight and low profile, especially when speed and precision are not important. Compared to other transmissions with rigid links, the range of motion can be arbitrarily long (e.g. 100's of meters) winches can be very strong if slow, and the mass is negligible when considering the length of actuation. The major caveat is that the winch cables are unidirectional. Cable-based robot systems have also been in existence for several decades, most notably the NIST robocrane [6] and the Skycam video systems now popular in sports arenas. However, these systems use just winches and cables and rely on a large frame to define the workspace of the robot, where as in our case, a prismatic joint is used in conjunction with the cable system, resulting in a much lighter weight system for a given workspace.

The Spiral Zipper includes a band of material that can join to itself helically to form a tube. The oldest similar concept comes from a 1939 patent for a lifting jack [7]. More recently, the Zippermast [8] and the Spiralift [9] are two commercially available systems that work similarly.

The Zippermast developed by Geo Systems Incorporated is a mechanism that uses three bands of metal that join in a triangle. The bands unspool from three separate coils in the base and interlock teeth to form an ad hoc beam. They come in different sizes, but the largest extends 7.5m and supports 25kg [9]. It is primarily used for an extension mast to get a high vantage point for sensors or antennae on a small ground robot [10]. This is a good example of a large extension ratio, but a beam with a triangle cross section is not as strong as a cylinder all else being equal.

The Spiralift developed by the company Gala Systems, is a custom theater stage lift. It employs a system of two steel bands, which form a rigid circular column. The first is a helical coil with teeth cut into the outside edge. The second band is thin steel with perforated edges, wound similarly as a photographic filmstrip [8]. By wrapping the band around the coil with the inner teeth locking the band together, it forms a very rigid column. The downside of this design is complexity and cost.

In contrast to these recent developments the proposed design requires only a single piece band and combines the basic idea of an expanding tube into a 3DOF positioning system with high strength to weight ratio. Whereas the previous are both stiffer and stronger, likely capable of higher precision, precision is not considered a priority in this case. That said, using these systems in place of the Spiral Zipper would still yield useful 3DOF positioning systems.

II. Operating Principle

The basis of the Spiral Zipper design is a long, thin band with mating teeth along both edges. A rotating mechanism we call a "slider" wraps the band into a helix while meshing the teeth on the bottom edge of one wrap with the teeth on the top of the wrap below. This helixed column is theoretically only limited by the length of the band.

The resulting column has exceptional performance in compression, but because of the zipping action, tension and moments applied to the column result in significant play especially on a long column. This Spiral Zipper column can be combined with a cable system to exploit the exceptional performance in compression. Cables on winches between a base and the distal end of the column as shown in Figure 1 can be used to position the end point while ensuring the column remains in compassion under nominal loading conditions.

The system can be broken into two major subsystems, the Spiral Zipper prismatic joint and the tether-gimbal rotational DOF sub-system.

A. *Spiral Zipper*

The main components of the Spiral Zipper are the band, the slider and driving mechanism.

1) The Band: A key element to the viability of the tube is formation of this helix. The geometry of the band in this helix defines many of the important performance metrics of the mechanism. We define the following:

H_B = Band Height
H_T = Tooth Height
β_I = Helix Incline Angle
P_B = Band Helix Pitch
D = Band Diameter
S_B = Arc Length of One Wrap
N = Number of teeth in a single Wrap (positive integer value)
P_T = Band Tooth Pitch
H = Overall Column Height
L_B = Length of Band

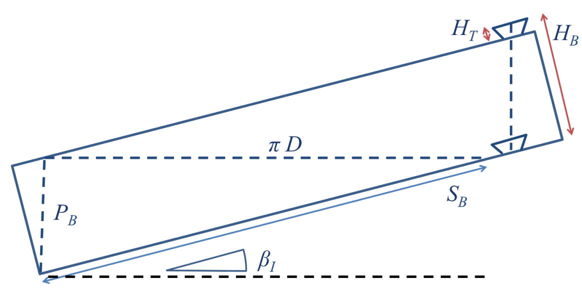

Fig. 2. A band laid out flat showing the dimensions of one wrap. Only one tooth is shown on the top and bottom edge.

Figure 2 shows a single unwrapped turn of the band. Assuming that the diameter and band and tooth heights have been chosen, the helix angle β_I can be calculated as follows:

$$\beta_I = \sin^{-1} \frac{H_B - H_T}{\pi D} \quad (1)$$

And it follows that the pitch can be calculated by:

$$P_B = \frac{H_B - H_T}{\cos \beta_I} \quad (2)$$

The tooth pitch can be set.

$$P_T = S_B/(N) \quad (3)$$

Extension height can be determined:

$$S_B = \sqrt{(P_B)^2 + (D)^2} \quad (4)$$

$$H = L_B/S_B P_B \quad (5)$$

The above equation assumes that the band has the male tooth positioned directly above its female mating slot when the band is at the pitch angle, as shown in Figure 2. Depending on the number of teeth desired, there is a quantized set of diameters that will work for a band.

As the band is wrapped, in order to maintain the structure, the top and bottom edges must not move as if they are rigidly connected. However, this connection must not be permanent allowing the wrapping and unwrapping process. Zippers do this by (dis)engaging teeth that are (dis)assembled through a motion local to an edge element typically perpendicular to the direction of nominal load. Each element in a closed zipper prevents this local motion of the element further down the chain, thus keeping the whole chain closed up to the end of the chain.

In the Spiral Zipper case, each tooth acts in the same way. The teeth are engaged by wrapping, which is a purely radial motion local to the tooth. Once engaged, for teeth to become disengaged, a radial motion is required. For any tooth not near the local wrap, a radial motion is coupled with a circumferential change as governed by Equation 4. This circumferential change cannot occur as the teeth prevent sliding circumferentially. This design results in a the band geometry that is mostly planar easing manufacture (explained in more detail in Section III-A).

2) Slider: The main purpose of the slider is the (dis)engagement of the teeth in the top and bottom edges when forming the tube as described above, just as a the slider on a clothing zipper is the part where the two seams are joined simply by pushing the two parts through the slider.

An exploded CAD drawing of a slider is shown in Figure 3. The band enters the slider in the structure on the left side of the figure and the tube grows out of the top. The band only needs to make contact with the slider in two parts, a lip at the bottom of the core that forms a helical ledge on which the band rests and the portion that joins the top and bottom edge (e.g. being squeezed by the slider body and the slider access door). Also just like a zipper, no other support other than the top of the tube and the slider portion is required to maintain the structure.

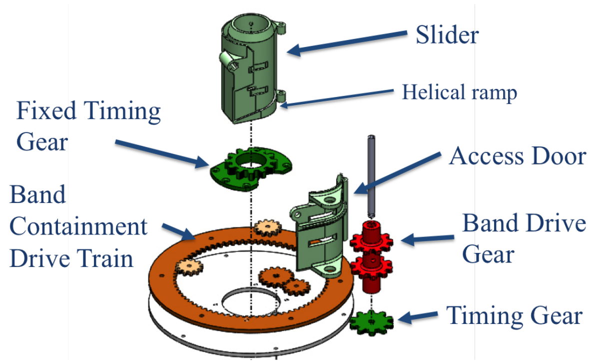

Fig. 3. A slider mechanism exploded view.

3) Driving mechanism: Forming the tube can be viewed in one of two ways depending on view point: by feeding the band into a non-moving slider so the tube spins as it grows, or a spinning slider, winding the band around a growing tube that does not spin. The spinning tube in the former case can make it awkward for end effectors or tethers mounted to the distal end. The latter case pushes complexity into the slider which is the approach in this design, however it is often conceptually easier to consider the non-moving slider.

Unlike a clothing zipper, the band must be pushed through the slider automatically. We do this with a band drive gear pushing on slots laser cut into the band. Conceptually, a motor mounted to the slider can drive this gear to drive the band into or out of the slider, extending or collapsing the tube. To prevent the tube spinning, we instead drive the slider around the growing tube while simultaneously driving the band in the opposite direction. This is achieved with gearing as illustrated in Figure 4. The band drive gear directly below the slider drives the band and simultaneously meshes with a gear of the same pitch as the slider radius fixed to the base. Thus as the slider rotates, the band drive gear pushes the band at the same surface speed in the opposite direction so the growing tube does not spin.

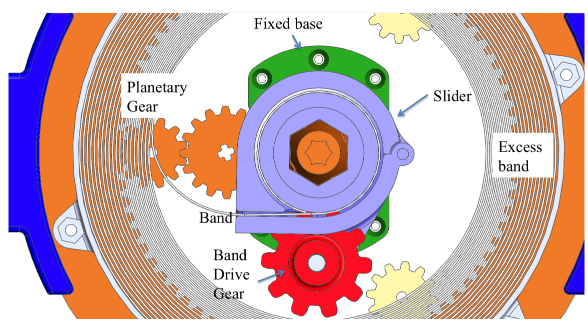

Fig. 4. Top view of the slider with gearing.

In addition, the band containment gear (Figure 3 which is the outer planetary gear shown in Figure 4 rotates the base housing the excess band material. This ensures that the excess band does not tighten and bind or jumble and snag while extending or collapsing (resp.).

B. Adding Rotational Degrees of Freedom

By mounting the Spiral Zipper onto a gimbal (Figure 1) or universal joint, we form an RRP robot arm configuration.

In this configuration the position of the end point can be controlled in a spherical coordinate form, as actuation and measurement are conveniently formed as pitch, roll, and radius. A full six DOF robot arm could be created by adding a wrist with 3 rotational DOF at the distal end.

The resulting system has a workspace that can be delimited as a portion of a sphere. The outer radius of the sphere is the fully extended length of the Spiral Zipper $R_o \approx H$. There is an inner unreachable volume delimited by the fully collapsed length of the Spiral Zipper $R_i \approx 2H_B$. The other limitations of the workspace are defined by the range of motion of the rotational joints. For example a universal joint with both DOF having range of 180^o would yield a hollow hemispherical workspace of radius R_o.

One nice characteristic of this workspace is that all points interior to this workspace are singularity free which notably does not occur with most standard articulated robot arms.

As explained in Section IV, the band works best in compression and may be relatively weak under moments. Instead of actuating the pitch and roll DOF with motors at the axis of the base, we can instead add tethers to the end effector and control position by varying the length of the tethers with winches. This is illustrated in Figure 5.

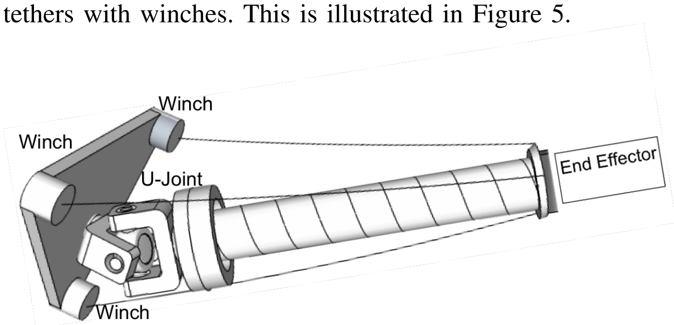

Fig. 5. A rendering of a Spiral Zipper mounted on a universal joint base with winch and cables.

If the rotational DOFs in the base are unactuated, (i.e. free to move), that end of the tube cannot support any moments. If there are no moments at the distal end and a force is applied where the tethers intersect (e.g. a load is being carried at the end effector), then there can be no moments in the tube. As a result there are, conveniently, only pure compression forces in the tube. This condition is similar to ideal statically determinate truss structures (e.g. truss bridges and cranes).

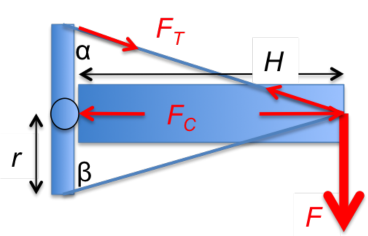

Fig. 6. A schematic view of an arm cantilevered holding a load at the end effector.

Figure 6 illustrates the condition of forces along the tethers and the tube when the beam is cantilevered with a payload under gravity represented by a force F. There are several trade offs visible from this figure. The tethers experience pure tension F_T (cables can only support tension), while the tube experiences pure compression F_C as required by the pinned end conditions of the beam assuming a massless beam.

This compressive force can become large as the angle between the tethers and the tube becomes small (e.g. the length of the tube H becomes large compared to the baseline distance to the winches r or $\alpha \to \pi/2$ or $\beta \to \pi/2$). In fact, the compressive force is exactly the ratio of the tube length to baseline distance in this particular case, $F_C = F\frac{H}{r}$

It can be seen that a smaller baseline yields larger compressive forces on the tube. The tradeoff here is that given a limited compressive stress (for example a critical buckling load of a column), larger cantilever loads require larger baseline profiles and this becomes severe as the column gets large. In addition, as the joint angles at the base α and β in Figure 6, get smaller, the tether's ability to apply torques about the base gimbal become reduced and the mechanical advantage becomes zero when $\alpha = 0$ or $\beta = 0$.

III. Implementation

The implementations can be broken into three parts, the Spiral Zipper band, the slider and the tether gimbal system.

A. The Spiral Zipper

Many prototypes of the Spiral Zipper were constructed however, two versions will be discussed, a 57mm diameter version (large) and a 17mm diameter version (small). Figure 7 shows the large column extending to full height. The full extent of the column made out of a 15m long plastic band was over 2.2m tall.

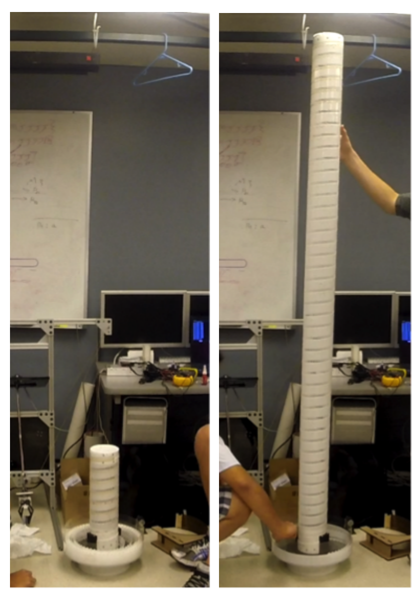

Fig. 7. The 57mm diameter Spiral Zipper starting to extend (left) and fully extended (right)

Most of the components in the Spiral Zipper other than the band and fasteners are 3D printed including the slider, gears, top tube cap and winding base.

The large version was created first to explore the feasibility of the design. The small one explored the scalability. The overall architecture of the design is basically the same as the larger one with a few changes. The height of the band was reduced from 50.8mm to 25.4mm tall. At a 17mm diameter, it has a more aggressive incline angle than the 57mm diameter one - 11.26 and 7.11 degrees respectively. This is advantageous because it extends or collapses faster given a fixed rotation speed. Because of the smaller diameter, the drive gear is more easily located on the outside of the tube where as the large diameters drive gear is on the inside.

Another design decision is where the drive gear should mesh with the band. It was observed that the band sometimes would bind in one direction of motion depending on whether the band was driven on the first or second wrap layer. A dual ganged drive gear (see Figure 8) was designed so that the gear meshed in the bottom two layers simultaneously alleviating this issue.

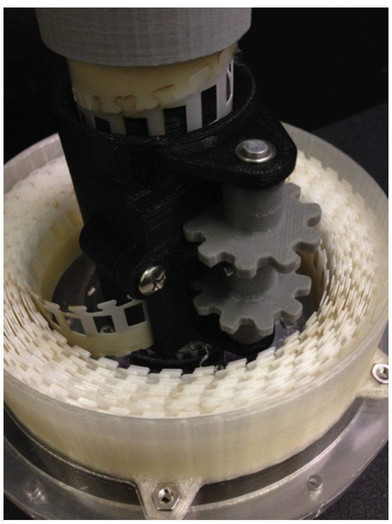

Fig. 8. Photo of the slider and drive mechanism for the 17mm diameter prototype

The prototypes bands have been made out of Acetal and ABS plastic. The bands were cut out of 4 inch and 2 inch wide, 0.02-0.035 inch thick strips. The plastics were chosen for flexibility, durability, low friction, and ability to be cleanly laser cut.

Manufacturing the long strips of the plastic band economically is important to the goal of making the system low cost. The two-inch wide plastic band is readily available in various lengths on a roll, but the challenge is precisely patterning the teeth on the edges. An ideal process would be a roll-to-roll band cutting operation. Custom machinery may be required for large quantities, but for prototypes, a laser cutter was used to cut successive portions of the band roll. For that the challenge is to hold the band flat and align the band in the laser cutter while maintaining registration of the band over successive refixturing and cutting operations. In our case, a custom jig solved both issues.

The shape of the meshing teeth has two functions. One is to ensure sliding circumferentially along the edges does not occur (thus changing radius and making the teeth disengage) while still being able to assemble at the slider. The other is to maintain engagement. Different shaped teeth can also effect the allowable tolerance that will result in slop in the tube (either in radius or in tension). Note that in the proposed system where the tube can maintain a compressive force the tolerance for motions in tension does not become a concern. Figure 9 shows some of the different teeth profiles and sizes that were tested.

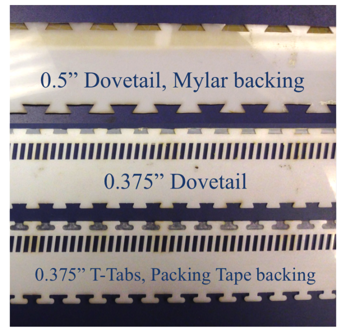

Fig. 9. Three of the dozen prototyped bands.

The designs that engaged well in the slider during assembly were ones with the most gap between the teeth in the direction parallel to the joint that didn’t jam in the slider. For example, the top band in Figure 9 didn’t work because it had large dovetail teeth whose corners would remain planar while the band curved and thus would catch on the slider.

Critical to the bands performance is keeping the teeth from disengaging (moving locally out of plane). A backing ribbon along one edge can help to ensure engagement. The tradeoffs in implementation include the ribbon thickness. It needs to be thin enough to ease entry in the slider and minimize differential stresses from the varied thickness of the band. It can’t be too thin to maintain structural integrity.

For the large diameter prototype the backing consisted of 0.08mm thick Mylar adhered with double sided tape. Proper assembly of these adhesive bands is also critical. Adhering the ribbon in a flat state would cause wrinkling and delamination as the band was wrapped, so adhesion on a curve was required (ideally with a curvature similar to that in the wrapped state). The double-sided tape was applied before laser cutting the teeth profile such that the adhesive was removed from between the teeth. The Mylar was then adhered to this tape.

The gear slots labeled in Figure 9 are used to drive the band in the slider. They are angled at the helix angle of the wrap such that they remain aligned with the axis of the tube when assembled (Figure 8). While a gear tooth is engaged in the slot, it actually will translate within this slot because of the feeding angle of the band. So the slots are taller than the thickness of the gear.

B. Tether-gimbal system

Figure 1 shows the smaller diameter Spiral Zipper mounted on a gimbal base supported by two tethers. For the three DOF system the three actuators (two winches and the Spiral Zipper actuator) are sufficient under gravity. In the configuration shown, gravity ensures that the tethers are always in tension. For convenience in this implementation, the tether routing is coplanar with the gimbal axis supported by an 80-20 frame. Dynamixel EX106 servos capable of 10Nm torque (not shown) were mounted with 50mm diameter spools to drive the winches and are capable of applying 420N of force along the tether with no load speeds of 238mm/s.

One set of applications for this arm is mounting it onto unmanned vehicles exploiting the low mass of the system. The US Army is interested in mounting the arm on an octorotor being developed at the Army Research Lab. In this case the frame of the vehicle would be used instead of the 80-20 frame. A mass analysis for this application using the prototype elements shown in Figure 1 is shown in Table I. A third winch is added similar to Figure 5 making the system over-constrained, but ensuring stability without consideration of gravity.

TABLE I
MASS BUDGET

Item	mass [g]
Band [1m reach]	107
Slider structure	64
Spiral Zipper servo	154
Gimbal	421
EX106 servo, (x3) [420N @ stall]	470
Gripper budget (e.g. simple hook)	200
Structure budget	200
Total	**1717**

IV. STRENGTH ANALYSIS

One of the main advantages of this system is the strength to weight ratio. That is the payload carrying capabilities of the arm versus its own weight. As shown in Section II-B, the payload depends highly on the compressive strength of the tube. In fact, since the servos and tethers can apply over 400N of pulling force, the main limitation will often be the compressive strength of the tube.

A. Compression Testing

The compressive load capacity of a slender beam is typically due to the critical buckling load $P_{CR} = 4\pi \frac{EI}{L^2}$ where E is the Young's modulus and I is the area moment of inertia for the tube. A hollow cylinder is optimal in terms of maximizing I for a given amount of material and uniform minimum buckling axis. However, since the Spiral Zipper is made up of a band with teeth (not a smooth cylindrical shell) local plate buckling may occur which is much more difficult to analyze. A more empirical analysis is warranted.

Compressions tests were conducted on an materials testing machine, MTS Criterion Model 43. This band was tested at different extension lengths up to the maximum testing length the MTS machine could accommodate - 850mm.

The small band with curved T-shaped teeth had an interesting failure mode. Compression forces bent the teeth outward causing all the teeth to interlace under pressure as shown in Figure 10 (right). As a result the integrity of the tube would still be intact, just with a somewhat smaller length.

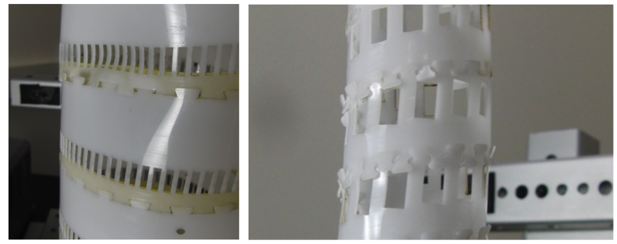

Fig. 10. Compressive failure modes. The 57mm diameter band locally buckled (left). The 17mm band teeth interlaced (right).

A 1.5m long, large diameter band was also tested. It was too large to fixture in the MTS machine so, it was tested using free weights. The column supported a maximum of 530N of weight before failure occurred. In the large band, the point of failure was delamination of the Mylar backing, which allowed one the teeth to slip inside the radius as shown in Figure 10. Once delaminated, the column would still function if the band was retracted and extended again past the failure point, but at a reduced capacity. The zipper mast (and in fact clothing zippers) recover similarly after failure [10]. After the backing was compromised, the column only supported approximately 350N before failure occurred in the already compromised locations.

The results of these tests are summarized in Table II. In this table, we include a theoretical buckling load for an ideal Euler buckling analysis case. It shows that up to an order of magnitude greater load may be a rough upper bound for the theoretical maximum compressive load of the geometry tested.

TABLE II
SPIRAL ZIPPER COMPRESSION TESTS

Diameter [mm]	114	33	33	33
Material	Acetyl	Acetyl	Acetyl	ABS
Band thickness [m]	8.9E-04	5.1E-04	5.1E-04	1.0E-03
Length [m]	1.50	0.85	0.64	0.24
Moment of inertia, I	5.1E-07	7.1E-09	7.1E-09	1.4E-08
Modulus, E [GPa]	2.90	2.90	2.90	3.00
Radius of gyration	0.04	0.01	0.01	0.01
Slenderness ratio (l/r)	37	73	55	21
P_{CR} @ full ext [N]	25914	1119	2007	28137
Actual failure [N]	**530**	**200**	**260**	**1345**

V. DISCUSSION

A. Advantages

The mechanism offers many key advantages. The first is the low profile exhibited by the large extension ratio. We were able to achieve a 14:1 extension ratio on the large band. The novel feature of this mechanism is no additional overhead needed to increase this ratio. One only has to add more band. Ratios of 100:1 should be feasible as long as the stiffness of the resulting tube is not compromised.

Another advantage is the strength to weight ratio. It is difficult to find devices designed exactly for the same purpose, however, we can compare a range of arms that were designed to be lightweight.

TABLE III

COMPARISON OF STRENGTH TO WEIGHT RATIO

Robot arm	Reach	F_{max}	M_{arm}	F_{max}/F_M	Ref.
Keemink et al.	0.09m	5 N	190g	**2.68** N/N	[2]
LWR 4*	0.79m	69N	8.1kg	**0.86** N/N	[11]
WAM 4DOF	1.0m	40N	25kg	**0.16** N/N	[12]
Spiral Zipper Sys.	0.85m	100N	705g	**14.4** N/N	

*estimated for first 3DOF

Table III lists several such arms. As a relative measure, we use the maximum force the arm can apply when fully extended F_{max} divided by the weight $F_M = M_{arm} \times g$. For most robot arms this number will be less than 1.0 and is usually less than 0.1 [13].

The Keemink arm is a small arm designed to be mounted on a small UAV. It is a parallel mechanism made with carbon fiber rods, small range of motion, small payload but also very light. The Kuka Lightweight Arm 4 (LWR4) is a high performance arm specifically designed to have a near 1:1 ratio between payload and weight[13]. The LWR4 has 7 DOF and the other systems only have 3 DOF, so to make the comparison more fair, we consider only the first 3 links of the LWR4. The Barrett WAM arm has been mounted on mobile robots and is also cable driven and high performance. Like the Spiral Zipper arm, the majority of the mass is located at the base. For the Spiral Zipper arm, the mass budget from Table I is used. While this does not include the mass of a frame (as the other systems do), for the mobile manipulation application, it is likely that mounting to the mobile base can replace a frame. The winch motors can each pull 420N so the payload limitation comes from the structural limitations. It is based on 1/2 the compressive strength of the tube, assuming a baseline $r = 0.42$m and the 33mm diameter tube shown in column 2 of Table II. This is conservative as later versions of the band made of ABS do not exhibit the same delamination issues resulting in higher compressive loads.

Also to be fair, speed is often a concern and the LWR4 and WAM systems are estimated to have 5 and 10 times (resp.) faster than the proposed system, for tip speed at no load, based on published data sheets. The Keemink arm's no load speed is approximately the same as the spiral zipper based on the Maxon RE10 motor they use.

B. *Concerns*

There are a few disadvantages that are inherent to the design that need to be considered. Keeping long bands (e.g. 15m) contained and orderly is a challenge. If the column breaks or the idle spool comes out, the band tends to get tangled or becomes very hard to work. Reassembling the column was made easier by the addition of an access door on the small diameter prototype. Maintaining the base rotation speed with the containment gearing was surprisingly challenging.

The 15m long band had major stability issues at the fully extended length. Each tooth has negligible play in the perpendicular direction to the joint in any one wrap; however, over many wraps, the play is accumulated. While still stable under compression, the column would lean from side to side causing large moments at the base. If the play is too large, the column teeth could also disengage at full extension.

The loading condition for a generic manipulator may not result in a pure force at the intersection of the mounted tethers. There may either be an offset force, or the load may present some moments at the end effector. This may then induce moments that must be supported by the Spiral Zipper tube. Tighter toleranced teeth than those presented in this paper will directly result in better performance under tension and moments. Later versions with tolerances of 0.02mm on the teeth significantly reduced this play, but the accumulation will still become an issue at long extensions and more structured testing under moment conditions needs to be developed.

VI. CONCLUSIONS

We were able to demonstrate promising prototypes for this Spiral Zipper based spherical robot and look to improve on the current performance of the column extension mechanism. As a robot arm mounted on a mobile base, having extension ratios of greater than 10 eases maneuvering and manipulation in cluttered environments.

For high strength to weight ratio actuation over long distances, the proposed system is typically an order of magnitude higher performing than other robot arm systems designed to be lightweight. Further improvements such as optimizing motors and servo's for specific torque as well as improving the backing tape of the bands for higher compressive strength is likely to greatly improve this ratio as well.

We are currently working on a possible applications mounting the arm on mobile bases including indoor aids for the elderly, and mounting to an octorotor for applications such as opening doors and manipulation of small objects. Combining the large reach with strong winch motors may also enable the manipulation of large objects such as furniture or spring loaded doors with indoor mobile robots.

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