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Knot Tying with Single Piece Fixtures

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Abstract— **Knot tying poses a challenge to robotic and human manipulation due to the need to regrasp a flexible string. Without sensing, it becomes nearly impossible to guess where the string is. However, by using a fixture, the string can be continually grasped during the entire tying process. We have developed fixtures for a simple overhand knot and a square knot, and have started developing a fixture for the two half hitches knot. We can tie knots in different types of wire and fishing line using these fixtures. In addition, we used a Cobra i600 SCARA arm to autonomously tie multiple overhand knots in sequence without sensing, using solder as the string-like material.**

I. INTRODUCTION

Knot tying is challenging because of the flexible nature of string and the need to regrasp the string. Humans use touch and vision to tie knots; most robotic systems, as explored in Section II, use multiple complex grippers and machine vision.

Several applications motivate autonomous knot tying. Basic examples include automation in the manufacturing process of textiles and fishing lures. An application that would greatly benefit from automated knot tying is suturing in minimally invasive surgery (MIS). In MIS, a few small incisions are made for the purpose of inserting manipulators into the patient. The surgeon must then accomplish all tasks using just these manipulators. In particular, manipulating suturing thread becomes very difficult. Our system requires significant work to adapt it for suturing, and we may have to fundamentally redesign our fixtures to fit the requirements of MIS.

Fixtures have been used to simplify robotic carton folding [1]. Stamping sheet metal with dies has been used heavily in industrial fabrication for many years. Significant additional work has been done on fixturing and automatic designing of fixtures for rigid bodies, beginning with Brost and Goldberg's algorithm [2].

In knot tying, a fixture makes it possible to grasp the string along its entire length, avoiding the problem of regrasping. Our fixtures exploit the different responses caused by pushing and pulling on a piece of string. The fixtures (referred to as knot boxes) consist of a smooth tube curved into the shape of the knot. Disregarding junctions, the outside surface of the curved tube is always solid. During a pushing motion, the string follows this outside surface. The inner surface of the curve has a thin slice removed along its entire length, which opens up into a hollow inner region in the center of the box, the knot extraction region. When pulled, the string passes through this slice in the tube wall into the extraction region. At this point, the string can be tightened into a knot and removed through one of the holes in the knot box.

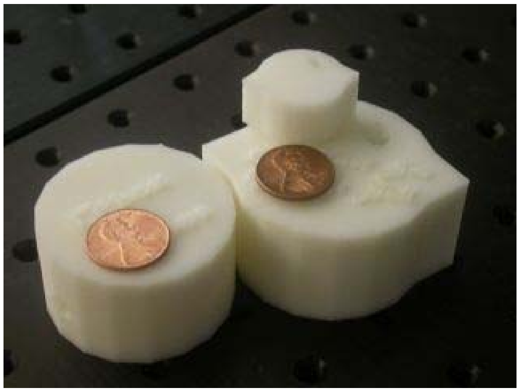

Fig. 1. Square knot (left) and overhand knot (right, 2 sizes) fixtures

We have developed knot boxes for three different knots (Figs. 1 and 2). The most basic is the overhand knot. This fixture can be used in two ways. Pushing a single wire into it will simply tie a knot in the wire (Fig. 2(d), left). Simultaneously pushing two wires through will tie both wires together into the same knot, effectively joining the wires (Fig. 2(d), center). We have also created a scaled down version (45% in each dimension) of the overhand knot box, with the exact same internal structure. The next is the square knot, which allows us to more securely tie two wires together (Fig. 2(d), right). Finally, two half hitches are used for securing a wire to a fixed object, such as a pole. The two half hitches knot box is currently being refined, and it is not yet fully functional. The knot boxes all work on a variety of materials, including thin wires and fishing line.

Based on our observations, we are able to make several statements regarding constraints on the knot boxes. We have observed that the best tubes are those which have a constant or gradually increasing curvature, with some upper bound on curvature. Also, we know that if the entire hollow interior of the knot box is topologically equivalent to a sphere, then there exists a path that the string can follow to tighten and extract the knot. However, this does not guarantee the string will follow any such path.

In addition, we have used the overhand knot box for

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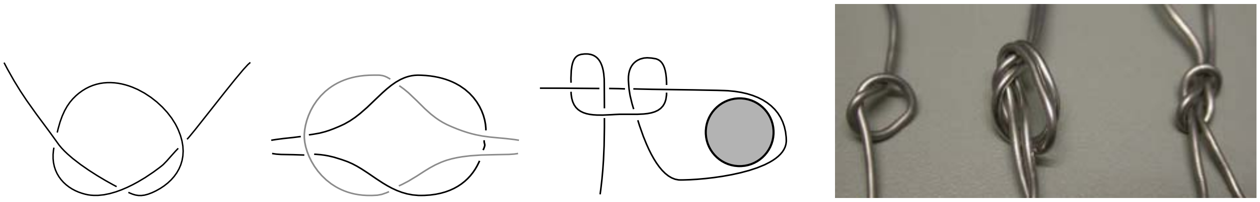


(a) Overhand knot (b) Square knot (c) Two half hitches (d) Knots tied by manually using the knot boxes (overhand, double overhand, square)

Fig. 2. Diagrams of the knot types, with knot examples

autonomous knot tying. A Cobra i600 SCARA arm has been fitted with a custom manipulator that can both grip and cut wire. We have been using solder for our experiments, as it is fairly flexible, but also capable of maintaining a shape, which makes its behavior more predictable. The system is capable of pushing the solder through the knot box, cutting the knotted portion away from the spool, and extracting the knot. This entire process can be repeated without human intervention to produce multiple separate knots in sequence.

II. Related Work

While we are not the first to tie knots autonomously, our system is considerably less complex than others. Knot tying was first explored by Inoue and Inaba using a 6+1 DOF robot arm with stereo machine vision [3]. Takamatsu created a system that could learn to tie a knot by observing a human tying one [4]; however, they do not seem to have extended this work to actually having a robot tie a knot. There has also been significant research in the area of medical robotics, particularly involving suturing during surgery [5]. Kang and Wen developed the EndoBot [6], a system designed to assist surgeons in minimally invasive surgeries. Their system includes algorithms for autonomously tying knots while suturing. Phillips, Ladd and Kavraki created a simulator capable of handling realistic rope, with suturing explored as a possible application [7]. Pai used Cosserat rods to simulate thin strands, such as sutures [8]. Saha, Isto, and Latombe developed a string model and motion planning algorithms for tying simulated knots [9], [10]. In addition, there are many patents for various devices to assist in knot tying. The patents all involve complex devices with moving parts, and are used for many applications, from tying fishing line [11] and shoelaces [12], to suturing [13].

III. Knot Box Design

The knot boxes are designed to exploit the difference between pushing and pulling a string. When pushed, a string in a curved tube will tend to follow the outside edge of the tube. When string is pulled, it tends to converge to the shortest path between the points at which the tension is being applied, subject to any obstacles in the way.

A knot box is first based on a tube in the shape of the desired knot. This knot shape is expanded to avoid self-intersection. At this point, it is possible to tie a knot by pushing string through the knot tube. However, the knot cannot be removed without dissolving or breaking the knot box. If we can extract the knot by cutting the fixture and separating the pieces, string insertion becomes much simpler, as there is only one path for the string to follow. A second design step is needed to solve this problem if we want the fixture to be one solid piece.

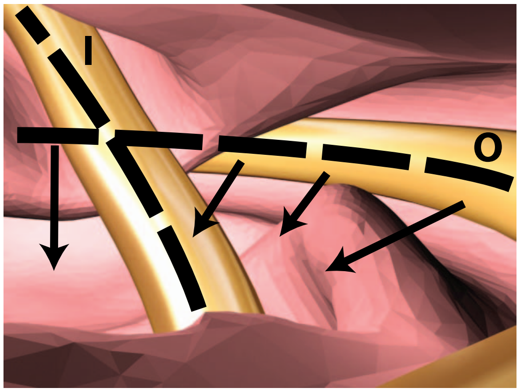
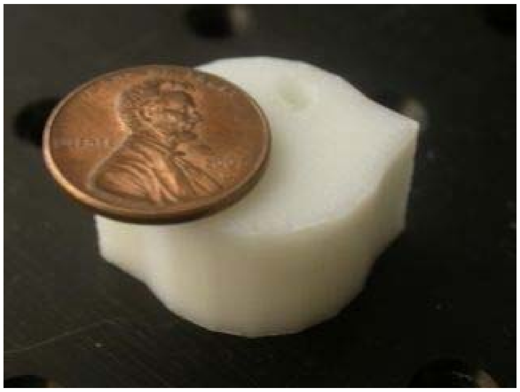


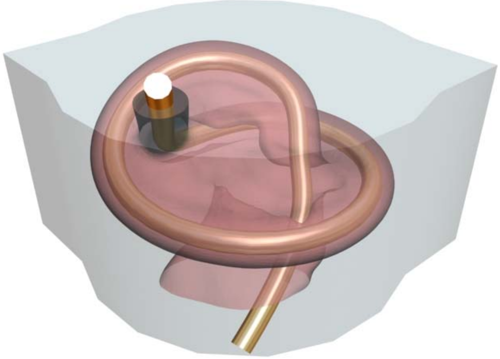
Fig. 3. Junction where outer wire (O) must cross inner wire's tube

String moves to the inside edge of a curved tube when it is pulled. The next logical step for making the box reusable is to remove this inside edge, and to provide a hollow interior region in the box for tightening and removing the knot. When an outer loop of string needs to cross an inner piece of string, the inner tube needs to have a cut around its entire circumference to allow the outer string to cross through the inner tube. In Fig. 3, this cut is visible from the center of the image to the lower left, behind the left wire. This creates an opening on the outside edge of the inner tube, which can serve as an alternate path out of the inner tube when string is being pushed through it. The key to avoiding this pitfall is to make the cuts perpendicular to the inner tube, and to make them as narrow as possible, as in the figure.

We employed an iterative process to develop the knot boxes. At each iteration, the initial knot tube was created in 3ds max as a NURBS curve. The curve was then converted into a tubular mesh, and imported into SensAble's ClayTools. We used a PHANTOM Omni haptic interface to simplify the process of carving out the knot extraction region. The completed shape was imported back into 3ds max, and subtracted from the main knot box shape (typically a cylinder). The resulting model was then rapid prototyped using a Stratasys



(a) Physical knot box (miniature version)



(b) 3D model

Fig. 4. Knot box for an overhand knot

FDM 2000. Fig. 4 shows a comparison of the 3D model and the prototype. At this point, we tested the knot box and redesigned it as needed.

A. Observations

While developing and experimenting with the knot boxes, we made several observations of the way string behaves. The knot boxes depend on the ability to push string at a point some distance from the end of the string (up to 25 cm with the current boxes). This is only possible if the string is capable of transmitting axial force all the way to its end. Two main factors act in opposition to proper axial force transmission. If the string is compressible, it may start to compress rather than transmitting force to its end. There is no simple way to deal with this, so we have avoided materials that compress, and we assume that the materials we use exhibit no compression for analytical purposes.

The second problem arises from buckling. When string is pushed, it tends to buckle out to a side. This behavior makes it problematic to push regular (e.g., cotton) string through a tube, such as those in the knot boxes. Regular string tends to buckle repeatedly along its length, which reduces its ability to transmit force axially. However, wire, fishing line, and other materials with some resistance to bending work well in the knot boxes, as these materials buckle less frequently.

We have also observed that it becomes harder to push string through the tube as the number of contacts with the tube walls increases. Buckling increases this number of contacts, which may eventually stop the string from making any forward progress, as the tubes are frequently quite long, with the potential for many contacts.

B. Curvature Constraints

During the iterated design steps that were required to perfect the knot boxes, we were able to observe possible failure modes. Frequently, the wire would get to a certain point in the tube, after which it would refuse to move further (or would only do so with great difficulty). This was usually caused by a turn in the tube being too tight, which was exacerbated by rough patches introduced by the FDM process. The FDM machine lays down material in horizontal layers that are 0.01” thick. In regions where the knot tube is close to horizontal, this will result in a step-like pattern in the tube, which can snag the end of wire passing through the tube. Putting a loop in the end of the wire before inserting it usually resolved any issues with these steps, but did not resolve the curvature issue. As discussed above, friction from multiple contacts plays a role in preventing forward motion in sharp curves. Hence, we believe that there is some maximum curvature beyond which the string or wire will not traverse the tube. The specific curvature is dependent on the material properties of the wire or string. We plan to use a string model to try to determine this maximum curvature in the future.

Most wires tend to have some degree of shape memory. This causes problems when the wire is exiting the knot box after completing the last loop. We observed that it was generally not possible to simply put a straight segment from the end of the last curve to the exit, as the wire would tend to keep curving through the cut on the inside of the straight tube, leading it somewhere back into the knot box. This also occurred with the fishing line, which had a curved shape from being spooled. This led to the conjecture that by maintaining constant or increasing curvature throughout the tube, we could avoid any difficulties posed by wire memory. The design has to respect the memory effect when the curve changes direction as well. If the curve changes direction, the wire will try to keep following the old direction. The cut on the inside of the tube must be oriented accordingly to prevent the wire from exiting the tube.

C. Topological Constraints

Once string has been threaded through the knot box, the knot must be tightened and extracted. In order for this to be possible, we must ensure that the tightening knot will not become wrapped around any portions of the fixture. We can impose a topological constraint that is necessary (although not sufficient) to prevent any portion of the fixture from being tied into the knot.

In order to be able to remove the knot from the fixture without breaking the fixture, the volume swept by the string as it tightens into the knot must be topologically spherical. We can ensure that this is the case by making the entire

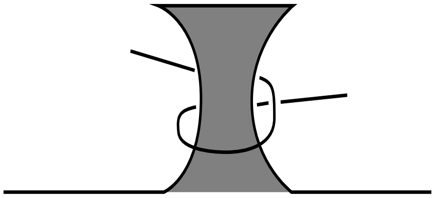


Fig. 5. Obstacle preventing extraction

interior region of the box topologically spherical. It is possible for the interior to contain columns that make the interior toroidal, provided that the swept volume remains spherical. However, such columns are unnecessary and undesirable.

This is not a sufficient condition for extraction, as it is possible to have obstacles that do not make the interior of the box toroidal, but yet still cause the knot to become stuck. For example, if there is a spool-like shape in the fixture, the knot can wrap around it with no possibility of extraction (Fig. 5). This suggests that a sufficient condition for successful knot extraction requires the interior to not contain any concavities, in addition to the already stated topological constraint. Not all concavities are bad, but if they are positioned incorrectly, they can prevent the knot from tightening and being extracted. Our existing knot boxes defy this second constraint, as they all have some concavities. However, these are typically minor, and they are carefully positioned such that they do not cause the knot to become caught. All of the knot boxes do satisfy the first constraint, which is particularly critical for knots involving multiple tubes (square knot and two half hitches). The multiple tubes must be joined appropriately to ensure that the interior is topologically spherical.

IV. AUTONOMOUS KNOT TYING

The autonomous knot tying system is built around an Adept Cobra i600 SCARA arm, which has 4 DOFs plus a gripper. The gripper is outfitted with jaws that have sandpaper attached to them for better gripping ability. The jaws have knife blades attached to them at the bottom to allow the gripper to also function as a pair of scissors. The knotbox is mounted on its side in a clamp. The solder is fed in from a spool mounted on the vertical rod of a lab stand. The solder passes through a wooden block with a hole drilled in it, which provides the robot with a known location for one end of the wire (the knot box entrance provides a known location for the other end). The entire system is pictured in Fig. 6.

The greatest challenge in autonomously handling any flexible material is knowing where it is located, particularly in the absence of sensing. While solder is not as flexible as string, it will still tend to droop when suspended over a long distance. In our setup, the solder is suspended between the wooden block and the knot box over a distance of approximately 5 cm. The amount of droop is negligible over this distance. As a result, we have a very good idea of where the solder will be at all times, even without sensing.

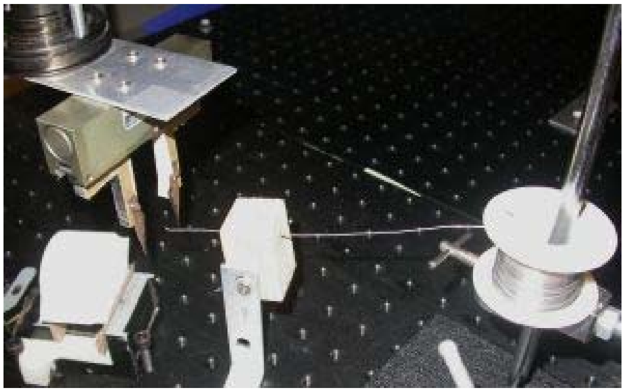


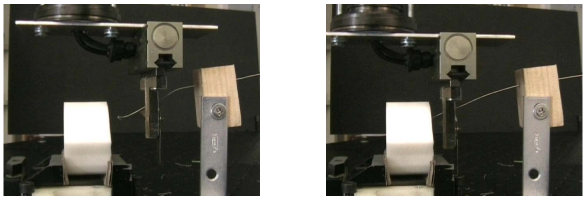
Fig. 6. Autonomous knot tying setup

A second challenge specific to our setup stems from the fact that cut solder has a fairly sharp end, combined with the rough step-like regions introduced by the prototyping process. The sharp end of the solder tends to catch on the edges of these steps as it is being pushed through the tube. During manual operation, this can usually be overcome by pushing the solder or wire in and out rapidly, and eventually the vibration will cause the wire to get past the step. Using vibration effectively requires some force sensing to tell when the solder is stuck. We attempted to overcome this in the absence of sensing by having the robot arm push the solder some small distance x into the box, and then pull it back out a distance $.75x$. However, as there is still no force sensing, if the solder does not get over the step during the vibration, the arm will try to keep pushing, and the solder will buckle between the gripper and the knot box, leading to failure. The other solution that works very well during manual operation is to fold over the end of the solder, forming a tiny loop that slides past any bumps in the tube with ease. The robot uses both methods (vibration and loop forming) to ensure success in knot tying.

The actual process is pictured in Fig. 7, and the steps are as follows:

1) Cut the solder to put the end in a known position (Fig. 7(a)). This cut takes place slightly more than a gripper width from the wooden block, allowing us to grip the solder as closely to the block as possible. This gives us the best probability of gripping the solder at the correct height within the gripper.
2) Pull the solder away from the block by about 2.5 cm. This provides space for the spinning motion in the next step.
3) Spin the gripper about 130° about a vertical axis located at the center of the jaws, which creates half of a loose loop of solder around one of the jaws of the gripper (Fig. 7(b)).
4) Back the gripper out of the loop, raise the gripper, spin it back around, and reposition it so that the loop is inside the jaws.
5) Close the gripper on the loop, which squeezes it together into the small, tight loop required for pushing


(a) Cut solder (b) Create loop


(c) Insert loop (d) Push solder

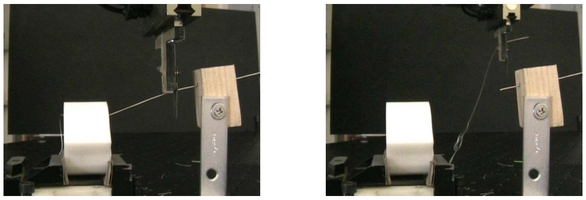

(e) Cut solder (f) Extract knot

Fig. 7. Autonomous Knot Tying


Fig. 8. Knots tied by the robot arm

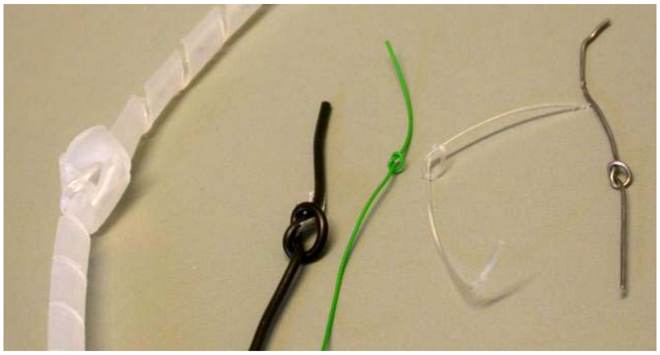


Fig. 9. Overhand knots in different materials tied manually using the knot box (R to L: .032” solder, fishing line, 30 and 22 AWG wire, wire loom)

the solder through the knot box.

6) Use several short motions to insert the start of the solder into the knot box (Fig. 7(c)). The solder is initially pulled horizontally into the loop forming location. However, the knot box entrance is lower, which requires us to pull the solder downward. Short motions ensure that the solder settles into a more natural position between grasps, which prevents the robot from introducing undesirable bends into the solder.
7) Repeat the vibration-like motion described above many times, until the end of the solder has gone about 5 cm out the other end of the knot box (Fig. 7(d)).
8) Cut the solder near the wooden block to free the knot, and to place the end in a known position for the next knot (Fig. 7(e)).
9) Pull the solder from the insertion side of the knot box, which causes the knot to form (Fig. 7(f)). The resulting knot is pulled off to the side and dropped.
10) Start over from step 2 to begin creating the next knot.

V. RESULTS

Using solder as the material, we are able to tie approximately one overhand knot per minute using the automated system. It should be possible to increase this speed, as we are running the robot arm at less than 50% of its full speed due to technical limitations of our setup. The completed knots are shown in Fig. 8. For the overhand knot, it is possible to position the knot at different distances from the ends of the wire depending on which end of the wire is pulled. For example, pulling only the leading end will place the knot near the following end, and pulling only the following end will place the knot near the leading end. Positions in the middle can be attained by pulling the two ends proportionally.

Under manual operation, it is possible to tie knots much more quickly. An overhand knot can be tied using the knot box in as little as 15-20 seconds. More materials can also be knotted by manually pushing them through the knotbox (Fig. 9), including

1) 0.025” diameter solder
2) 0.032” diameter solder
3) 25 lb fishing line
4) 22 AWG single strand wire
5) 30 AWG single strand wire wrap wire
6) 5mm diameter wire loom

VI. OPEN PROBLEMS

There are several avenues of future exploration for knot tying with fixtures. One of the most obvious is the development of fixtures for additional types of knots, and in the process, trying to determine the limitations of this technique. At a certain point, it seems that the tube might become too long to effectively allow the wire to be pushed. Multiple loops will also make the design more complex, as it becomes necessary to handle more junctions in the extraction paths. Applications such as suturing in MIS require careful tightening and positioning of the knot to avoid damaging fragile tissue, and our current knot boxes do not provide a sufficient degree of control, particularly for square knots, which are required for suturing. It may be necessary to create multiple knot boxes to allow different portions of the knot to be tightened separately with finer control.

The use of a 4-DOF arm for autonomous knot tying is still overly complex. It should be possible to use just a set of rollers to insert the wire, combined with a simple cutting mechanism. A second set of rollers at the exit from the box would allow tightening and extraction of the knot. In the current system, buckling tends to happen immediately after the solder has been regrasped, when the arm is at the furthest point from the knot box. This suggests that with rollers near the box, the risk of buckling will be significantly reduced. Also, the vibratory motion can be done at a much higher speed, which should enable even wire with a sharp edge to slide past any obstructions in the knot tube. For these reasons, rollers should be more effective even though they cannot form a small loop at the end of the wire to make insertion smoother.

A natural extension of research into additional knots is the development of algorithms for automatically creating knot boxes. Given a basic description of the knot structure, such as a Gauss code, it should be possible to create splines and to expand them until they fit the appropriate curvature constraints. A second algorithm can take the spline, convert it to a volumetric representation, and carve out the regions necessary for knot extraction. The simplest method is to pick a center point for the final knot, and to remove voxels in lines from this center point to the insides of the knot curves. However, the algorithm would need to take junctions into account, making it more complex than this naïve version.

Minimal fixtures provide another area of potential research. Most of the material in a knot box is simply filler. The wire should only need to contact in a few key points to create the correct bends. Assuming that we could suspend small bent tubes in space, how few tube segments are necessary to guide a string into the shape of a knot? With this knowledge, it might then be possible to design LEGO-like tube pieces that could be combined in different ways to produce different knots.

The knot boxes can also be modified to support different materials. We have begun to explore tying knots in actual string, which cannot be pushed due to excessive buckling. We have considered using compressed air to blow string through the knot box, and have done some preliminary experiments in this area. With a small knot tied in the end of a string to serve as a plug for the air to push on, we have used air to push the string through the current overhand knot box to form a knot. This process is not very repeatable, as the string frequently slips out of the main tube into the interior of the box. We have only succeeded in tying knots in string a few times. By alternately pushing a short amount of string and blowing into the miniature knot box, we have also tied a knot in thinner string, although this is also not very repeatable yet. To improve repeatability in both cases, we can try to reduce the cut in the tube to the smallest possible size, reducing the likelihood that the string will slip out of the tube when being pushed by air. A second option is to design a fixture that has just the knot tube cut into it, with no extraction region. In this case, the fixture would have to split into two pieces to allow removal of the knot. However, the string would also be guaranteed to follow the correct channel. We are working on designing two piece fixtures, and have made some progress in tying knots in string using them.

VII. CONCLUSIONS

We have successfully used fixtures to tie different knots in multiple materials, exploiting the fundamental difference in pushing and pulling string. The knot boxes have proven to be robust and scalable. Although only stiffer, wire-like materials are reliable at the moment, there appears to be promise in using air to aid in tying knots in more flexible materials, such as regular string. This line of research suggests that there might be possibilities for using small puffs of air or CO_2 and a miniature knot box to assist in tying sutures in MIS. We have also successfully programmed a robot arm to use one of the fixtures to create knots. While the robot is currently limited to one knot and one material, we believe the system can be extended to work with different types of materials, and with different knot boxes, particularly if the robot is simplified to just several sets of rollers for feeding wire.

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