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DEVELOPMENT OF A SELF-DECOUPLED WIRE-DRIVEN ROBOTIC UNIVERSAL JOINT TOWARDS MEDICAL APPLICATION

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ABSTRACT

Robots for surgery and rehabilitation have emerged and are gaining popularity among patients and medical doctors with their obvious benefits, such as overcoming obstacles from human users' physical restraints, reducing physicians' workload, and enhancing the efficacy of medical treatment. The development of medical robots meets two challenges related to their special application environments, including sterilization hazards and size/weight limitation. Medical robots (e.g., surgical robots) usually need to have close contact with human skin or organs, which need to be sterilized. However, chemical or heat sterilization on the robots poses an inevitable risk of damage on the motors, sensors, and other electronic components. The size of the surgical robot needs to be compact to gain access to surgical sites. The rehabilitation robots that patients wear have to limit their size and weight. Wire-driven actuation is a potential solution to solve these issues by avoiding the use of bulky mechanical gears and links and locating the electronic components far away from the sterilization environment. This paper presents the development of a novel wire-driven universal joint for medical robot design. With its special structure, this robotic joint has self-decoupled kinematics which can simplify its control system and increase motion accuracy. Benchtop experiments are conducted to verify the functionality of this joint and the effectiveness of its self-decoupled kinematics.

Keywords: Medical robot, universal joint, wire-driven, self-decoupled

1. INTRODUCTION

Along with the rapid development of a combination of technologies (motors, materials, and control theories) and the advances of medical imaging and sensing, robotic technologies for medical application have been gaining significant growth and advance[1]. Categorized by the application fields, medical robots can be mainly divided into surgical robots, rehabilitation robots, prostheses/orthoses, and hospital service robots[2]. With the advantages in precise and quick motion, long duration, and capability to access complex environments, medical robots have gained increasing acceptance among both patients and medical professionals. For instance, since laparoscopy surgeries were developed in the mid-1980s, this type of surgery is swiftly accepted among patients with its fewer and smaller incisions,

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improved cosmetics, reduced postoperative pain, less bleeding, and shortened recovery time[3]. However, compared to open surgery, laparoscopic surgery loses haptic feedback and impairs visibility from the surgical sites, making the surgical procedure complex and increasing the surgeon's physical and mental stress[4]. The development of robotic technologies in biomedical imaging and sensing can largely reduce the influence of these drawbacks and reduce surgeons' workload. Currently, robotic technologies have been applied for a variety of surgical procedures including cardiac, colorectal, general, gynecologic, head and neck, thoracic, and urologic surgery[5].

Although medical robot has numerous benefits for patients and medical professionals, its development meets several technical challenges related to its application environment. First, as most medical robots need to have close contact with human skin and internal tissues/organs, sterilization on these parts of the robot is indispensable which has a high potential to damage the electronic components of the robot[6]. Secondly, the application environment has a strict requirement on the robotic size and weight. Surgical robots usually need to gain access to human abdominal cavity through small incisions or natural orifices, thus requesting compact size and maintaining sufficient power. However, there is a fundamental conflict that conventional actuators with small size could not provide high power[7]. Finally, the dexterity of medical robots is compromised by the lack of diversity of robotic joints. Utilizing different joints could largely increase the dexterity of robotic manipulators and keep a compact size[8]. However, the choices for available joints are limited by the actuation methods (e.g., it is challenging to develop a rotational joint with pneumatic actuation.)

These challenges can be addressed by utilizing wire-driven joints. Wire drive enables a remote actuation that the electronic actuators and sensors can be located far away from the work sites, avoiding potential damage from the sterilization. In addition, as these actuators and sensors are located in the places other than work sites, it reduces the size and weight of the robot in work sites. Wire-driven actuation has been widely used in robotics, especially medical robots with its benefits as mentioned above. Nevertheless, most wire-driven actuations are used for parallel robots or snake-like serial robots that the robotic joints are usually passive (unpowered). The parallel robots have a bulky size as they usually have several serial chains to support a big platform. The snake-like robots, instead of driving robotic joints individually, use wires to drive all the links or the flexible whole robotic body[9], making the actuation system underactuated. The desired position trajectories of the snake-like robot with this underactuated system can easily be deflected by the load present at the end link or by any external disturbing force on the robotic body. Active wired-driven joints can enhance the benefits of wire-driven actuation with the compactness of structure and robustness to sterilization and maintain a precise motion control. Active wire-driven joints are difficult to develop for robotic application as motion coupling results from the cable routing, whereby the cables driving one of degrees of freedom (DOFs) affects the rotation of other DOFs, making precise motion control extremely challenging[10].

Our lab is dedicated to developing various wire-driven joints for medical robotic application, including passive articulated robotic joints, active prismatic joints, and active rotational joints[11-13]. In order to increase the diversity of joints in medical robots for dexterity enhancement, this paper presents a novel active universal joint driven by wire actuation. The joint has unique self-decoupled kinematics that one of the DOFs moves will not affect another DOF, significantly simplifying the control system and increasing motion accuracy. Kinematics analysis was conducted. And benchtop experiments were conducted to verify its functionality and the effectiveness of the decoupled kinematics.

2. METHOD

This paper presents the development of a novel wire-driven universal joint with self-decoupled kinematics. This section illustrates the structure design, kinematics analysis and control system.

2.1 Structure design

A universal joint is a joint connecting two rigid links whose axes cross each other to provide two DOFs (named yaw and pitch in this paper). Universal joints have been extensively used in different medical robotic applications to mimic natural motion, such as human wrist and finger motion[14]. To enhance the benefits of wire-driven actuation in medical robots, this paper presents a novel active universal joint driven by attached wires.

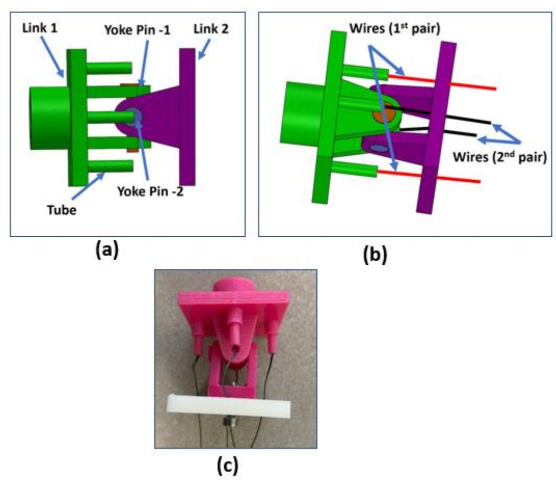
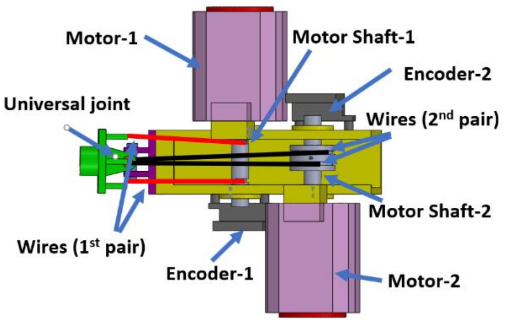
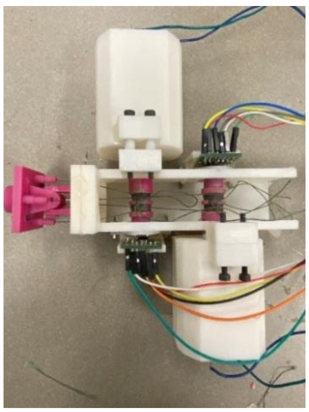


FIGURE 1: (a) JOINT STRUCTURE; (b) WIRES ON JOINTS; (c) PROTOTYPE

The structure of the universal joint is as shown in Fig.1. It consists of two links, connected by two yoke pins intersecting at a common center. At the upper link (*Link 1*), there are four cylindrical tubes each with a center hole in 1 mm diameter for wire routing. The four straight tubes have equal length, and they are extended up to the center of the rotation joint as shown in Fig.1 (a). This feature is significant as it is the main contribution to creating the self-decoupled kinematics. Two pairs of wires are fixed on *Link 1*, pass the four cylinders and *Link 2*, and end up on the shafts of two actuators. For each pair of wires, one is twined clockwise on the shaft of its actuator, and the other one is twined counterclockwise on the same shaft. In this way, one actuator can control one DOF of the joint for two-direction movement.



(a) CAD MODEL OF ASSEMBLED JOINT



(b) ASSEMBLED PROTOTYPE
FIGURE 2: ASSEMBLED JOINT

The components of the joint were fabricated in additive manufacturing, and a prototype was assembled as shown in Fig 2 (b). In this prototype, we designed the size of the link platform in a square shape with 35 mm for each edge. There are no electronic components on the joint. The DC motors are used as actuators and located away from the joint. When this universal joint is in practical application, the size of the joint can be adjusted as needed and the electrical components can be placed even further away from the joint.

2.2 Kinematic analysis

The purpose of this kinematics analysis is to find the mathematical relationship between the joint rotation and the length change of the wires.

A schematic diagram is extracted from the 3D model. As can be seen in Fig. 3, the initial lengths of the two wires for the yaw and the pitch are as shown in Fig. 3(b). If the joint is driven to rotate for yaw motion, the length of the wires for yaw will be changed (red), while the length of the wires for pitch will not be changed as the tube makes the pitch wires rotate around the center (See Fig.3 (c)). Therefore, the yaw movement will not affect wire length for pitch motion, and a similar pattern will appear for pitch motion, creating decoupled kinematics.

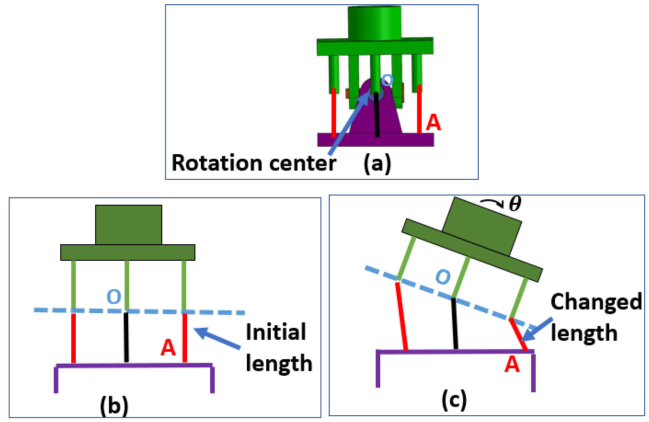


FIGURE 3: (a) CAD MODEL OF THE JOINT; (b) SCHEMATIC OF WIRES IN ORIGINAL POSITION; (c) SCHEMATIC OF WIRES AFTER ROTATION

A geometrical model is extracted from the schematic model as shown in Fig. 4. At the initial position when there is no rotation or $\theta = 0$, the length of the wire is denoted as $AC = l_1$ which is also the distance between the center of the joint and the face of *Link 2*. r represents the distance between the joint center and the tube center. l_2 represents the distance between *Point O* and *Point A*.

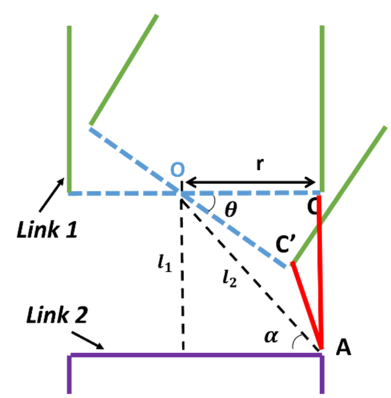


FIGURE 4: GEOMETRICAL MODEL OF THE ROTATION

When the joint rotates an angle θ clockwise from the joint center, the wire length will be deformed as AC' shown in Fig. 4.

Now $\angle AOC = \alpha$ from the geometry. So, we can obtain,

$$\alpha = \tan^{-1}\frac{l_1}{r} \tag{1}$$

$$l_2 = \sqrt{{l_1}^2 + r^2} \tag{2}$$

The position of $C'(r, -\theta)$ and the position for $A(l_2, -\alpha)$ in the polar coordinate with O as the origin will give us the length for AC' as:

$$AC' = \sqrt{{l_1}^2 + 2r^2 - 2r\sqrt{{l_1}^2 + r^2}\cos(\theta - \alpha)} \quad (3)$$

So, the total change of the wire length ΔL can be expressed as

$$\Delta L = l_1 - \sqrt{{l_1}^2 + 2r^2 - 2r\sqrt{{l_1}^2 + r^2}\cos(\theta - \alpha)} \quad (4)$$

In the pair of wires, one gets shortened on one side, the other is elongated on the other side, making an equal length compensation of the wire wrapped and unwrapped around the motor shaft for one DOF movement. In addition, we can observe from the equations above that the length change is only associated with the angle motion θ and other constant parameters from the prototype design. This is the same for pitch motion as well. Thus, one DOF motion does not influence another motion with this novel structure.

2. 3. Control system

A control system is designed with a PID position controller as shown in Fig. 5. The setpoints are the degrees of desired rotation (yaw and pitch). The length changes of the wires are calculated with the kinematics analysis in Section 2.2, and then are transformed as the rotations of motor shafts which are proportional to the change of wire lengths. Each motor shaft is installed with a co-axis magnetic encoder to get position feedback for the actuator. The gains of the PID controller were tuned with the Ziegler-Nichols approach[15], followed by minor manual adjustments.

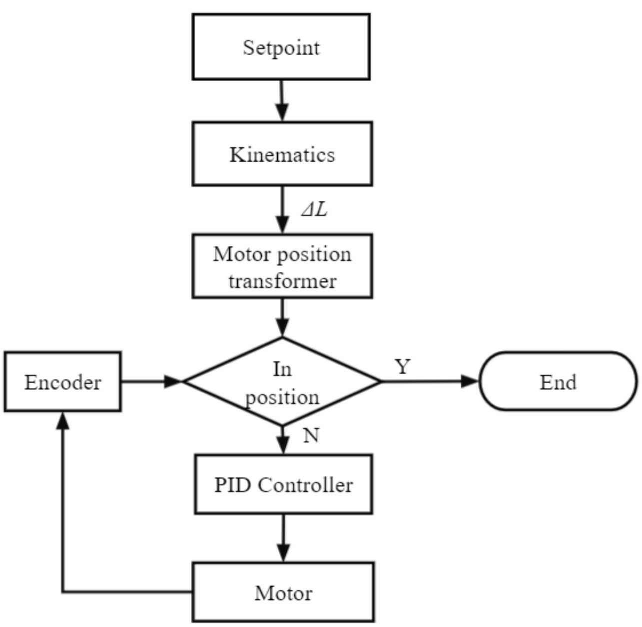


FIGURE 5: DIAGRAM OF THE CONTROL FLOW

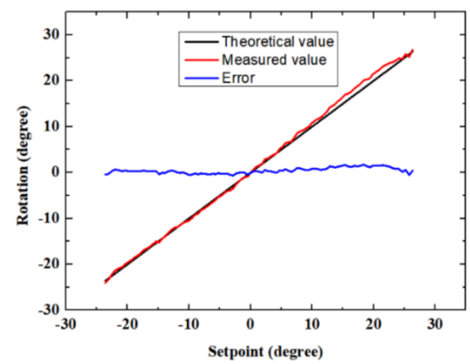
3. EXPERIMENT AND RESULT

3.1 Experiment setting

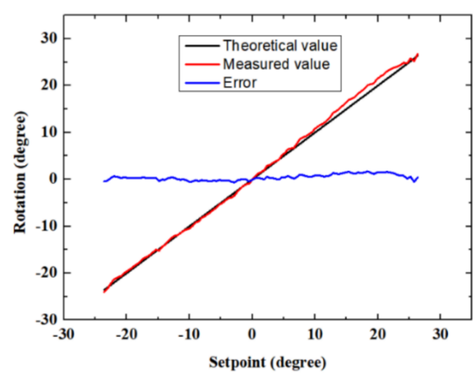
Two experiments were conducted to verify the functionality of the universal joint and its decoupled kinematics. Arduino Mega is used to build the controller. The robotic joint is set vertical to the horizontal surface, and an inclinometer (NSDOG2-002) is installed on the platform of *Link 1* to obtain ground-truth data. The first experiment is to verify the functionality of the robotic joint by driving the joint to rotate from -25 degree to 25 degree for both yaw and pitch motion. The desired rotation will be compared with ground-truth data measured by the inclinometer, and the errors will be used to evaluate whether the function of the joint is realized. The second experiment was conducted to evaluate the self-decoupling function of the kinematics. One of the DOFs (yaw or pitch) will be driven to rotate with desired setpoints, and another DOF motion will be set static (zero setpoints). The phenomenon that the static DOF does not move as expected demonstrates no influence from the moving DOF, verifying the effectiveness of the decoupling function.

3.2 Experiment results

As can be seen in Fig. 6, the motion of the robotic joint tracked the desired rotation with small errors for both yaw and pitch movement. The average errors of the position for yaw and pitch are 0.52 degree and 0.58 degree respectively. Compared to the large movement range, these small errors are relatively small, demonstrating that the design and control system of the wire-driven joint realized its function.



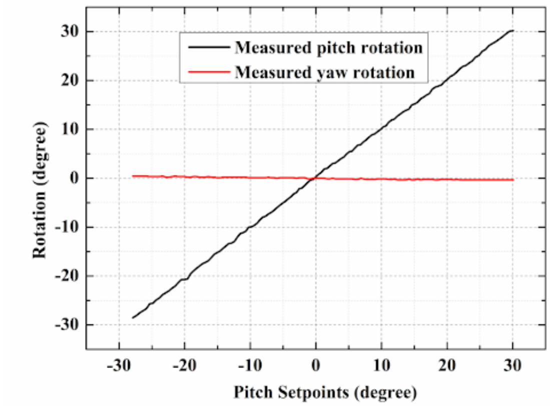
(a) PITCH ROTATION



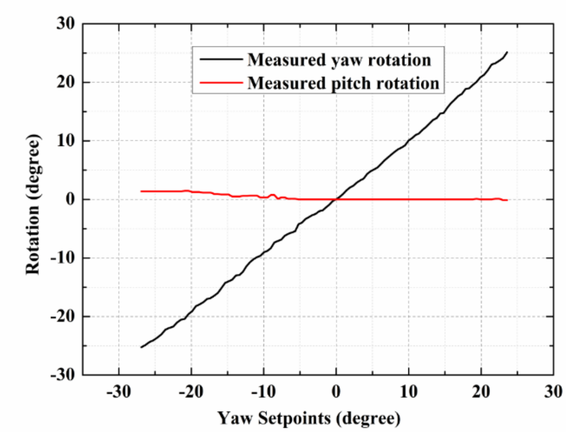
(b) YAW ROTATION

FIGURE 6: RESULTS FOR TWO ROTATING DOFS

As can be seen in Fig. 7, there is no motion of yaw as the pitch motion is driven. The same static state for pitch is shown as yaw motion is driven. This demonstrates the motion of one DOF is not affected by another DOF in this universal joint, demonstrating the effectiveness of the self-decoupled kinematics.



(a) ROTATING PITCH AND STATIC YAW



(b) ROTATING YAW AND STATIC PITCH
FIGURE 7: RESULTS FOR ONE ROTATIONAL DOF AND ONE STATIC DOF

CONCLUSION

The application of medical robots emerges and gains popularity among patients and medical doctors. However, the development of medical robots meets two major challenges related to its special application environment, including sterilization hazards and size/weight limitation. To address these challenges, this paper presents a novel wire-driven universal joint for future medical robot development. With a wire-driven actuation, electrical components can be located far away from the worksites, creating robustness to sterilization hazards and maintaining a compact structure. The universal joint presented in this paper also has self-decoupled kinematics which can simplify the control and increase the motion precision. Experiments were conducted and the results demonstrated the functionality of the universal joint and the effectiveness of the decoupled kinematics, proving the feasible application of this novel design.

Future work will explore solutions to tighten the wires conveniently. We will also integrate this universal joint with other types of wire-driven robotic joints to create a medical robot with high dexterity. Experiments will also be conducted to verify the functionality of the robot and improvement will be processed to move wire-driven medical robots for a practical application level.

REFERENCES

[1] Beasley, R.A., 2012, *Medical robots: current systems and research directions.* Journal of Robotics. **2012**.

[2] Zhou, J., Ma, X., Xu, Z., and Qi, Z. *Overview of Medical Robot Technology Development*. in *2018 37th Chinese Control Conference (CCC)*. 2018. IEEE.

[3] Shen, T., Hennings, D., Nelson, C.A., and Oleynikov, D., 2018, *Performance of a multifunctional robot for natural orifice transluminal endoscopic surgery.* Surgical innovation. **25**(4): p. 364-373.

[4] Zahraee, A.H., Paik, J.K., Szewczyk, J., and Morel, G., 2010, *Toward the development of a hand-held surgical robot for laparoscopy.* IEEE/ASME Transactions on mechatronics. **15**(6): p. 853-861.

[5] Diana, M. and Marescaux, J., 2015, *Robotic surgery.* Journal of British Surgery. **102**(2): p. e15-e28.

[6] Tzemanaki, A., Fracczak, L., Gillatt, D., Koupparis, A., Melhuish, C., Persad, R., Rowe, E., Pipe, A.G., and Dogramadzi, S. *Design of a multi-DOF cable-driven mechanism of a miniature serial manipulator for robot-assisted minimally invasive surgery*. in *2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob)*. 2016. IEEE.

[7] Shen, T., Nelson, C.A., and Bradley, J., 2019, *Design of a model-free cross-coupled controller with application to robotic NOTES.* Journal of Intelligent & Robotic Systems. **95**(2): p. 473-489.

[8] Wu, L. and Tadesse, Y. *Musculoskeletal system for bio-inspired robotic systems based on ball and socket joints*. in *ASME International Mechanical Engineering Congress and Exposition*. 2016. American Society of Mechanical Engineers.

[9] Yang, C., Geng, S., Walker, I., Branson, D.T., Liu, J., Dai, J.S., and Kang, R., 2020, *Geometric constraint-based modeling and analysis of a novel continuum robot with Shape Memory Alloy initiated variable stiffness.* The International Journal of Robotics Research. **39**(14): p. 1620-1634.

[10] Sang, H., Meng, J., and Yun, J. *Kinematic analysis of a class of multi-DOF tendon-driven minimally invasive surgical instruments*. in *Proceedings of 2011 International Conference on Computer Science and Network Technology*. 2011. IEEE.

[11] Shen, T., Nelson, C.A., Warburton, K., and Oleynikov, D., 2015, *Design and Analysis of a Novel Articulated*

Drive Mechanism for Multifunctional NOTES Robot. Journal of Mechanisms and Robotics. **7**(1): p. 011004.
[12] Chowdhury, A.M.B., Cullado, M.J., and Shen, T. *A Wire-Driven Multifunctional Manipulator for Single Incision Laparoscopic Surgery*. in *Design of Medical Devices Conference*. 2020. Minneapolis, Minnesota, USA.
[13] Chowdhury, A.M.M.B., Cheng, J., Cullado, M.J., and Shen, T. *Design and Analysis of a Wire-Driven Multifunctional Robot for Single Incision Laparoscopic Surgery*. in *the ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. 2020.
[14] Bajaj, N.M., Spiers, A.J., and Dollar, A.M., 2019, *State of the Art in Artificial Wrists: A Review of Prosthetic and Robotic Wrist Design.* IEEE Transactions on Robotics. **35**(1): p. 261-277.
[15] Ziegler, J.G. and Nichols, N.B., 1993, *Optimum Settings for Automatic Controllers.* Journal of Dynamic Systems, Measurement, and Control. **115**(2B): p. 220-222.