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A Novel Delta-Type Parallel Mechanism with Wire-Pulleys

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***Abstract*— It is well known that parallel mechanisms have several advantages, namely high power, rapidity and high stiffness. However, their workspace is limited due to interference of each chain. In our previous work, to expand the workspace of Delta mechanisms, ball bearings were employed instead of ball joints. Although this allowed a relatively wide workspace to be achieved, the clearance gap of the ball bearings introduced undesirable flexibility, while mechanical limitations persisted. In this paper, to tackle these problems, a novel parallel mechanism with wire-pulleys is proposed. The basic structure of the new mechanism is the same as that of the conventional Delta mechanism, but wire-pulleys are employed instead of a parallel four-bar mechanism. The key feature of the wire-pulleys is its lack of mechanical limitations. A prototype has been designed and developed, which achieves a wider workspace and reduced backlash. In addition, the total parts quantity has declined by more than 25%. Fundamental experiments show its potential.**

I. INTRODUCTION

Over the last few decades, many parallel manipulators have been developed and utilized in various fields. The benefits of parallel manipulators are well-known, namely their rapidity, and high power and stiffness. However, these properties are also strongly dependent on employed parallel mechanisms. For example, Stewart-platform type parallel robots are suited for applications requiring high power and accuracy because of the simple mechanism and linear actuator properties [1]. However, the inertia of the actuator causes the fast motion ability to decline. HEXA-type parallel robots can achieve fast motion, because all the actuators are fixed to the base [2]. However, the relatively complex mechanism and rotary actuators make both accuracy and power insufficiency. Although a pantograph-type parallel robot achieves a wider workspace, its complex mechanism and the inertia of the actuators limit the advantages of the parallel mechanism [3]. These three parallel robots are representatives of 6-DOF parallel robots. Unfortunately, the workspace is limited due to the interference of complicated chains. To overcome this problem, redundancy is introduced in some parallel robots [4], [5]. As might be expected, additional actuators increase its cost.

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Fig. 1. Photo of a prototype

Conversely, Clavel proposed a 3-DOF parallel robot named Delta [6]. The Delta, with 1-DOF hand, has become the most popular parallel mechanism and the industry standard. It is mainly used for pick and place tasks, due to its fast motion ability; achieved via fixed rotary actuators at the base. However, its workspace is limited by the range of movement of ball joints. To expand its workspace, ball bearings are installed instead of ball joints [7], [8]. Currently, the Delta with ball joints is becoming a popular parallel mechanism in the field of haptic interface [9]. However, the clearance gap of the ball bearings reduces the stiffness of the mechanism. To ease this problem, springs can be employed at ball bearings.

In this paper, to increase the workspace of the Delta mechanism, a novel parallel mechanism utilizing wire-pulleys is proposed and a prototype has been designed and developed as shown in Fig. 1. Not only does the proposed mechanism achieve a wider workspace, it also eliminates backlash. In addition, the total number of parts can be reduced by more than 25%. Furthermore, its wider workspace introduces new singularity, never previously achieved in conventional Delta

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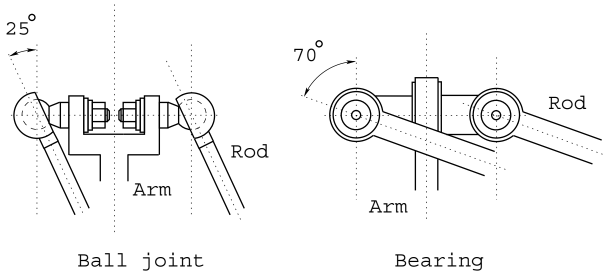

Fig. 2. Movable area of joints

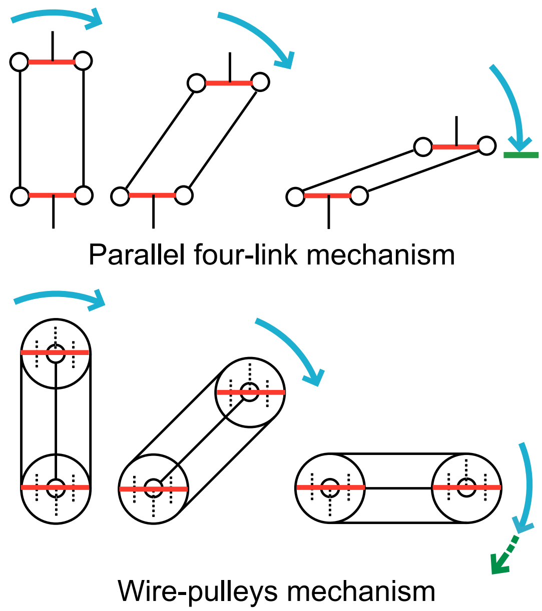

Fig. 3. Movable area of mechanisms

mechanisms. Naturally, this is not a desirable outcome, but reveals a new academic issue.

This paper is organized as follows. Section II proposes the basic idea of the novel parallel mechanism with wire-pulleys. In Section III, details of the mechanical design are explained, and the assembly procedure is presented. Section IV describes the control system. In Section V, a developed prototype shows its features, including singularity, and a fundamental experiment shows its feasibilities. Finally, Section VI concludes our paper.

II. A Novel Parallel Mechanism with Wire-Pulleys

The workspace of the Delta mechanism depends on the angle between the arm and rods [10]. As shown in Fig. 2, the angle of inclination of a ball joint, at around ± 25 degrees, depends on the mechanical limits within the range of motion of the ball joints. Conversely, a bearing system can incline by around ± 70 degrees. As a result, the Delta with ball bearings

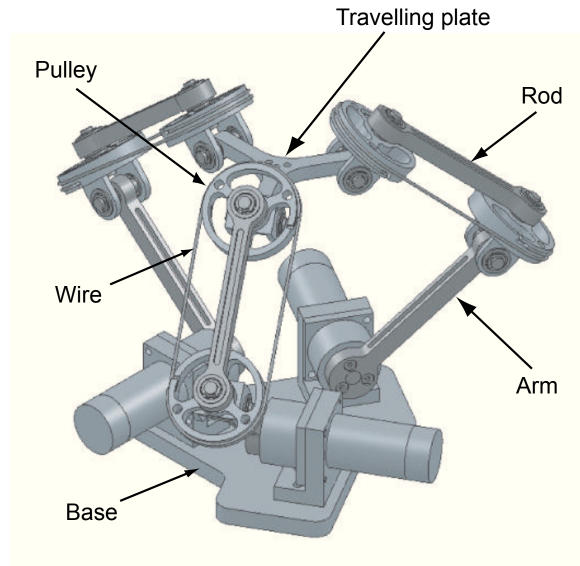

Fig. 4. Details of a prototype

can achieve a wide workspace. However, it should be noted that each rod is subject to torsion in the Delta with ball bearings, hence the rods must be designed to withstand such torsion. Meanwhile, this torsion of the rods is eliminated in the Delta with ball joints, which is a major advantage of the conventional Delta mechanism.

Here, we would like to emphasize the ongoing mechanical limitations of the ball bearing system. To remove these limitations, we propose a novel parallel mechanism with wire-pulleys. In the Delta mechanism, three sets of parallel four-bar mechanisms are key components which contribute 3-DOF translational motion with constant orientation. Conversely, wire-pulleys also function on a parallel four-bar mechanism as shown in Fig. 3. In addition, they have no mechanical limitations. Accordingly, we employ a wire-pulley mechanism instead of the four-bar mechanism, which thus allows a wider workspace to be achieved. Furthermore, the required number of parts is fewer than that of the four-bar mechanism. Fig. 4 shows the proposed parallel mechanism, the advantages of which are listed as follows:

1) Wider workspace
2) Fewer parts
3) Eliminates backlash

Details of the third advantage will be mentioned in the next section. Conversely, the proposed mechanism has the following disadvantages:

1) Small available area of traveling plate
2) Torsion on rods
3) Reduced stiffness

The first disadvantage is caused by interference between

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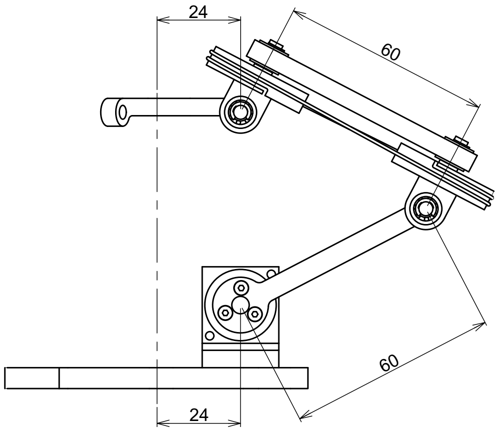

Fig. 5. Dimensions of the prototype

Fig. 6. Overview of developed wire-pulleys mechanism

pulleys and the traveling plate, although this can be eased by ensuring proper size and arrangement. The second disadvantage is the same as the case of the Delta with ball bearings. Hence, the rods must be designed to withstand such torsion. The third disadvantage depends on the stiffness of the wire. This means the stiffness of the end-effector can be customized by proper wires. In addition, a metal tape with higher stiffness can be utilized instead of wire. In this way, such problems can be mitigated using a range of proper approaches. Furthermore, we would like to emphasize that the third advantage outweighs the third disadvantage.

III. Mechanical Design

A. Overall Design

In our previous work, we developed a modified Delta mechanism using a ball bearing for the Skincare Robot [10]. In order to compare a new prototype with the previous Delta mechanism, the same mechanical parameters are employed. The lengths of both the arm and rod are 60 mm, while the diameters of both the base and traveling plate are 48 mm, as shown in Fig. 5. We would like to emphasize that the

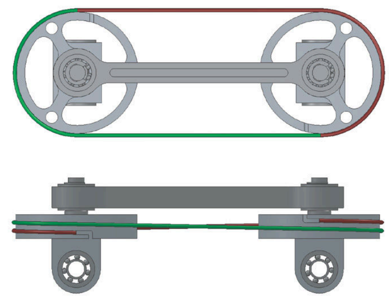

Fig. 7. Paths of the wire

number of parts in the new mechanism (167 parts) is fewer than that of the previous Delta (227 parts), representing a reduction exceeding 25%.

A combination of a harmonic gear and DC motor is utilized, just as in the previous Delta. The gear ratio of the harmonic gear is 100:1. In the near future, we will utilize the prototype as a small haptic interface following comparative study.

B. Wire-pulleys Mechanism

We design a simple and efficient wire-pulley mechanism as shown in Fig. 6. Pulleys are made of aluminum, while stainless steel is employed for rods, in order to help withstand torsion. Two stainless steel miniature wire ropes are employed to protect slip between wire and pulleys. As shown in Fig. 7, we decide on wire paths that avoid interference with each other.

The motion range of pulleys is restricted by ± 90 degrees. Although in practical terms, the wire-pulleys have no mechanical limitations, a singular configuration appears at ± 90 degrees as a parallel mechanism, which is why we restrict the motion range. We would like to point out that this restriction is just design policy. If the restriction were removed, a reconfigurable parallel mechanism would be obtained.

Although the pulley shaft is supported by two bearings, a cantilever type support is also adopted for simplicity, which means the wire tension introduces undesirable moment, as shown in Fig. 8. However, this also helps ease the clearance gap of the bearings and helps improve the stiffness of the parallel mechanism. In practical terms, the touch of the new mechanism is superior to that of the modified Delta mechanism.

C. Assembly Procedure

Usually, a wire tensioner is needed for wire-pulley mechanisms. Here, we introduce a special jig as shown in Fig. 9 to simplify the mechanism. Two blocks are connected by a linear guide and screw with a handle and two pins are fixed

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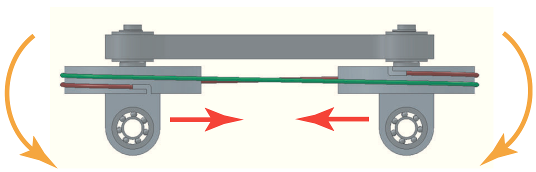

Fig. 8. Moment by wire tension

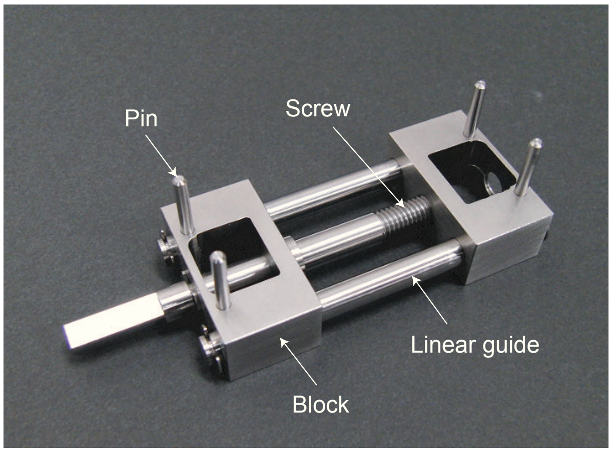

Fig. 9. A jig for assembly

to each block to fix the pulleys. The assembly procedure for wire-pulleys is as shown in Fig. 10.

(1) Reduced distance between blocks.
(2) Each pulley is fixed to each block with pins.
(3) Two wires hooked on chases of pulleys.
(4) Blocks set at proper distances corresponding to the lengths of rods.
(5) Rods installed and fixed by retaining rings.
(6) The completed wire-pulleys is removed.

A small clip is attached to the ends of wires to hook on chases of pulleys. The wire length should be precisely controlled to achieve proper tension. Accordingly, simple wire-pulley mechanisms can be designed.

It should be pointed out that the wire will loosen over time. However, no troubles have emerged to date, even more than five months since assembly. Its durability should be confirmed in future work.

D. Kinematics

The kinematics of the proposed mechanism are identical to the conventional Delta mechanism, meaning analytical solutions for both direct and inverse kinematics can be applied.

IV. Control System

The manipulator is driven by three Maxon motors (RE max 21, 6W) with Maxon motor drivers. An SH-4 control board (LEPRACAUN-CPU made by General Robotix, Inc.) and an I/O board (LEPRACAUN-IO made by General Robotix, Inc.) are employed for motor control. The OS of the control board is ART-LINUX, and it is connected to a host PC via LAN. The I/O board has 16 ch D/A and 16 ch counter. The control system is shown in Fig. 11. A 6-axis force/torque sensor will be installed in the near future, since we will use the prototype as a haptic interface.

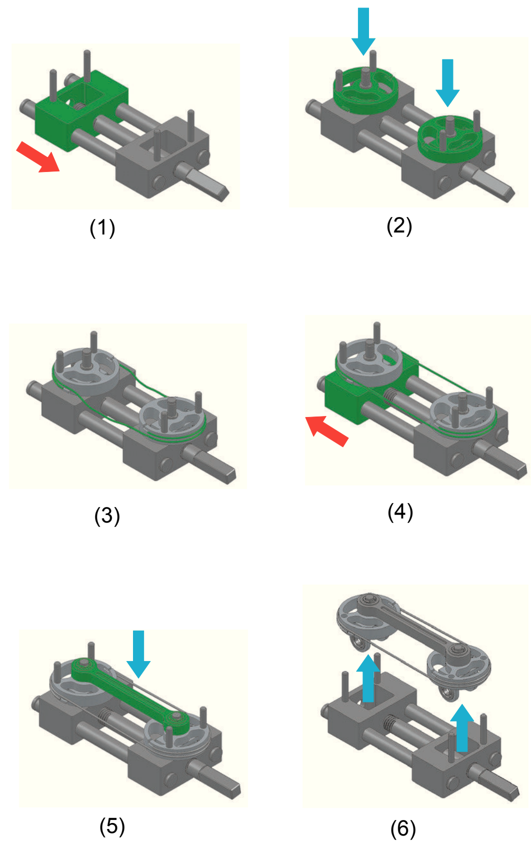

Fig. 10. Procedure for assembly with jigs

V. Experiment

A. Stiffness

As mentioned, the touch feeling of stiffness of the end-effector is harder than that of the previous one. This is related to the wire tension, which eliminates the clearance gap of ball bearings. It was pointed out that the elasticity of ball bearings reduces the stiffness of a modified Delta mechanism [11].

From the material mechanics perspective, the stiffness of wire-pulleys should be lower than that of the four-bar mechanism. However, for low-level loads like haptic interfaces, the stiffness of wire-pulleys is fully accepted. In addition, the lack of backlash helps enhance the appropriate feelings.

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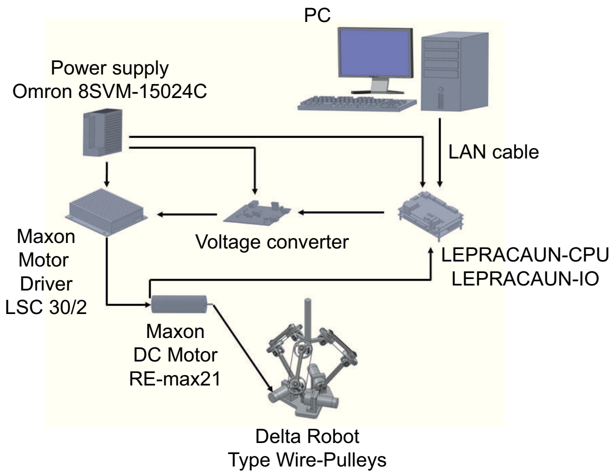

Fig. 11. Control system architecture

B. Singularity

The proposed parallel mechanism achieves a wide workspace, which means a singular configuration not seen in the conventional Delta mechanism emerges. In other words, the conventional Delta mechanism cannot achieve such a configuration. Fig. 11 shows singularity. It is clear that the singularity emerges when the joint axis attached to the pulleys becomes parallel, whereupon the orientation of wire-pulleys cannot be fixed. This is over-mobility singularity [2].

C. Fundamental Experiments

To confirm the feasibility of this prototype, fundamental motions are experimentally executed. Fig. 12 shows these motions. 3-DOF translational motions can be achieved with constant orientation, which is always parallel to the base.

VI. Conclusions

A novel parallel mechanism utilizing wire-pulleys is proposed. A prototype is also designed and developed, the feasibility of which is shown. The proposed mechanism achieves not only a wider workspace, but also a backlash-less property. As a result, stiffness of the end-effector is increased. In addition, the number of parts can be reduced by more than 25%. Furthermore, its wider workspace introduces new singularity, not previously seen in the conventional Delta mechanism, which reveals a new academic issue.

Stiffness analysis is under exploration. The results will emerge in a few months and help enhance the properties of the proposed mechanism.

Finally, we would like to emphasize that wire-pulleys can be applied to not only Delta mechanism but also various parallel mechanism. Our paper is first step into new frontier of the parallel mechanism.

Fig. 12. Singularity

VII. Acknowledgments

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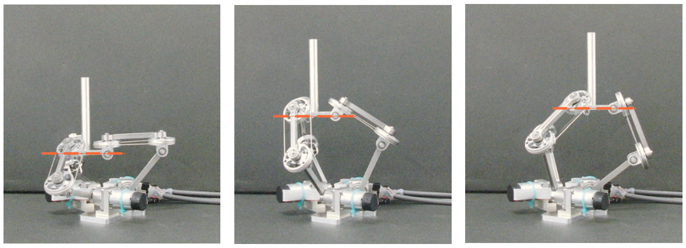

Fig. 13. Motions of the prototype

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