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Development of Upper-Body Humanoid Robot Using 3-US Parallel Link Mechanism

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***Abstract*— Humanoids that can mimic human movements are effective for avatar robots that are remotely controlled by humans. Conventional serial link manipulators can be used for the arms, but the waist of a humanoid affects the range of motion of the head and hands, and it must support the weight of the humanoid's upper body while moving. Therefore, we focused on the parallel link mechanism, which has higher torque and stiffness than the serial link mechanism. In this study, the 3-US parallel link mechanism with 3-DOFs of posture, which has been studied by the authors, is applied to a waist joint of an upper-body humanoid robot that has a range of motion similar to that of a human. We also develop a serial link arm robot with 7-DOFs and combine it with a waist joint as an upper-body humanoid robot.**

I. INTRODUCTION

For avatar robots that are remotely controlled by a person, humanoids that can mimic human motion are effective. Conventional serial link manipulators can be used for the arms, but the range of motion of the humanoid robot's waist greatly affects the range of motion of the head and hands. In addition, the waist must support the weight of the robot's upper body while moving, so high torque and stiffness are important in the design. To solve these problems, we focused on a parallel link mechanism. Compared to serial link mechanisms, the parallel link mechanisms are easier to achieve high stiffness, low inertia, and high precision, and many configurations (Stewart platform, DELTA, etc.) have been proposed so far.

Among them, a 3-UU parallel link mechanism with 2-DOF in posture, called Quaternion joint, has recently been proposed as a wrist joint for humanoid robots[1]. The 3-UU parallel link mechanism is almost the same as the one presented by Sugihara et al. as a zero-DOF mechanism that moves[2], [3], [4]. The Quaternion joint achieves the minimization of the tip weight by making the mass and inertia of the manipulator smaller than that of a human arm, placing the heavy actuators and reduction gears at the root of the arm, and using a tendon drive mechanism. A 3SU-UPU parallel mechanism has also been proposed for the shoulder joint under the name Cybernetic shoulder[5]. The structure is complex in order to realize 3-DOF.

3-RRRR parallel mechanisms with 2-DOF in posture have been developed from the constant velocity joint and marketed under the name iWrist [6], [7]. Another product is known as Omni-Wrist III[8]. These types of rotational parallel mechanisms are included in a family of 2-DOF rotational parallel manipulators (RPMs) with an equal-diameter spherical pure rotation (ESPR) [9].

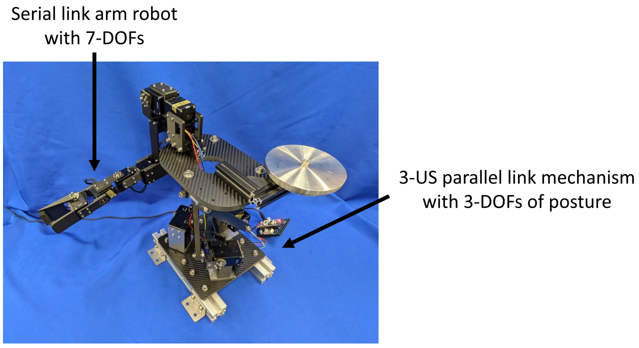

Fig. 1. Upper-body humanoid robot with 10-DOF (3-DOF for waist and 7-DOF for right arm)

However, these mechanisms themselves have 2-DOFs (roll and pitch), and to make a 3-DOF humanoid joint requires an additional mechanism for yaw rotation, such as adding a link inside the mechanism as in [1] or rotating the entire mechanism as in [5].

On the other hand, the review paper on wrist joints details the classification of serial and parallel from 1-DOF to 3-DOF [10] including the above studies. As one of 3-DOF mechanism, spherical parallel mechanisms (SPMs) with 3-RRR configuration and 3-DOF in posture, such as "The Agile Eye"[11], have been proposed. However, this mechanism is not suitable for use in a humanoid upper body because it has a structure in which the linkage extends outward, or the linkage members are concentrated in the center when posture changes, and therefore the linkage is not always centered in the center.

In this study, the 3-US parallel link mechanism with 3-DOFs of posture, which has been studied by the authors[12], is applied to a waist joint of an upper-body humanoid robot that imitates human motion. We also develop a serial link arm robot with 7-DOFs and combine it with a waist joint as an upper-body humanoid robot as shown in Fig. 1.

This paper is organized as follows. Section 2 describes the configuration of the upper-body humanoid robot. Section 3 describes the kinematics by numerical solution method with prioritized multiple targets for the redundant humanoid robot. Section 4 shows an experiment to verify the kinematics solution of the actual humanoid robot by performing a pick and place task. Finally, section 5 summarizes the paper.

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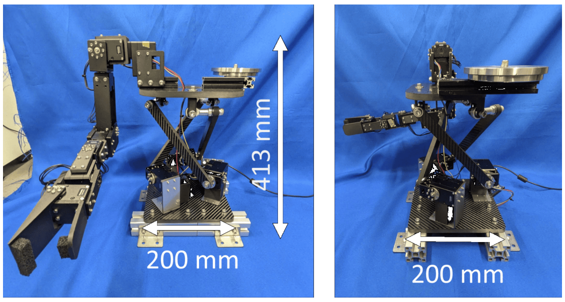

Fig. 2. Dimensions of developed humanoid robot (front and side view)

TABLE I

SPECIFICATIONS OF DEVELOPED HUMANOID ROBOT

Configuration	Parallel link mechanism for waist Serial link mechanism for right arm
Number of motors	11 (Dynamixel XM430, XM540)
Weight	6,420g
Software	MATLAB, Simulink, Arduino
Power supply	DC12V
Degree of freedom	10 (3 for waist and 7 for right arm)
Note	Serial communication

TABLE II

JOINT RANGES OF MOTION OF THIS ROBOT AND HUMAN

Joint	Axis	Robot [deg]	Human [deg]
Waist	Roll	$-55 \sim 45$	$-30 \sim 45$
	Pitch	$-50 \sim 45$	± 50
	Yaw	± 50	± 40
Shoulder	Roll	± 180	$-180 \sim 50$
	Pitch	$-200 \sim 20$	$-180 \sim 0$
	Yaw	$-180 \sim 60$	$-80 \sim 60$
Elbow	Roll	$-130 \sim 10$	$-145 \sim 5$
Wrist	Roll	± 90	$-70 \sim 90$
	Pitch	± 90	$-25 \sim 55$
	Yaw	± 90	± 90

II. UPPER-BODY HUMANOID ROBOT CONFIGURATION

The authors developed a 3-US parallel link mechanism in the previous study[12]. This parallel link mechanism is limited in translational motion, but has three degrees of freedom in posture. The arrangement is suitable for expressing the body motion of the human waist. Therefore, we constructed an upper-body humanoid robot that employs the 3-DOF parallel link in the waist and a 7-DOF serial link in the upper limb (right arm). To reduce the weight, carbon fiber reinforced plastic (CFRP), 3D printed plastic, and an aluminum frame were used for the links. The specifications of the developed humanoid robot are shown in Table I, and the typical dimensions are shown in Fig. 2.

Currently, the humanoid only has a right arm, so a weight is attached to the left side to balance the upper body.

A. Design of Waist Part

The kinematic diagram of the 3-DOF parallel link mechanism used for the waist part of humanoid robot is shown in Fig. 3. The 3D CAD model developed for the humanoid is shown in Fig. 4. The parallel link mechanism consists of a base plate, three chains, and an end effector. Each chain consists of a bracket, servo motor, frame, link 1, rod end, and link 2.

The base plate and end effector are made of acrylic, the blankets are made of stainless steel, the rod ends are made of carbon steel. Links 1 are made of CFRP, and links 2 are made of resin. Each chain is designed to have a universal joint (2-DOF) on the base plate side and a spherical joint (3-DOF) on the end-effector side. The servo motors, which are Dynamixel XM540s manufactured by Robotis, are located every 120° from the center of the base plate and are connected to the end-effector via the chain. Thus, there are three universal joints on the base plate side and three spherical joints on the end-effector side, resulting in a 3-US parallel link mechanism with 3-DOF.

If $M = 6$ is the DOF of the space, N is the total number of links, m is the DOF of each joint, and j_m is the total number of joints with m-DOF, then the DOF of the mechanism, G, is given by the following Gruebler's formula:

$$\begin{aligned} G &= M(N-1) - \sum_{m=1}^{M-1} (M-m) j_m && (1) \\ &= 6(5-1) - (6-3)3 - (6-2)3 && (2) \\ &= 24 - 9 - 12 = 3 && (3) \end{aligned}$$

Substituting the values based on Fig. 3, it can be confirmed that this parallel link mechanism has 3-DOF.

The coordinate system is defined with the center of the base plate as the origin, the vertical direction of the robot as the z-axis, and one of the three servo motors on the y-axis. By changing the angles of the three servo motors, the prototype 3-US parallel link mechanism can generate 3-DOF of rotation around the x, y, and z axes, as shown in Figs. 5 and 6. The ranges of motion of the human waist, shoulder, elbow and wrist are listed in the right column of Table II [13]. As shown in Table II, the range of motion of the human waist is -30 to 45 deg in flexion/extension (corresponding to the roll of the robot), ± 50 deg in lateral bending (corresponding to the pitch of the robot), and ± 40 deg in rotation (corresponding to the yaw of the robot). See in Figs. 7–9 for the definitions of motion. Based on previous studies [14], the dimensions of each link were determined to satisfy the above ranges of motion as shown in the middle coulmn of Table II.

B. Design of Right Arm

To emulate human arm motion, a serial link robot with 7-DOFs, which includes the shoulder, elbow, and wrist, was designed as shown in Fig. 10. The robot is driven by servo motors, Robotis Dynamixel XM540 and XM430. Two XM540s are used for the first and second joints and five XM430s for the remaining joints. A gripper can be attached as an end effector. In Fig. 10, the servo for the end effector is included, in total it consists of 8 servos.

III. HUMANOID ROBOT KINEMATICS BY NUMERICAL SOLUTION

Forward and inverse kinematics of 3-US parallel links are difficult to solve analytically. Moreover, as an upper-body

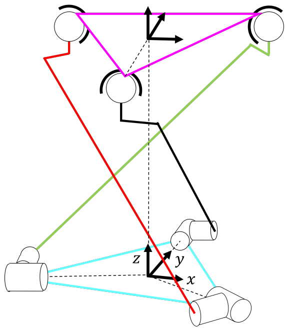

Fig. 3. Kinematic diagram of 3-US parallel link

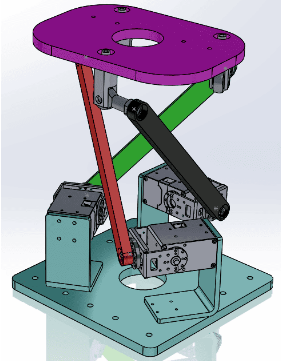

Fig. 4. CAD model of 3-US parallel link

Fig. 5. Rotation around yaw axis

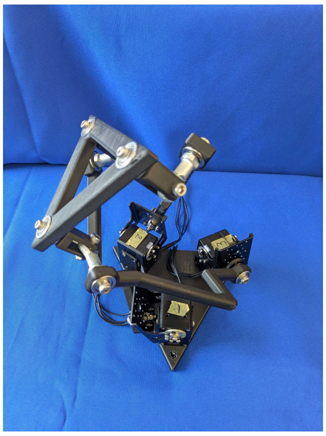

Fig. 6. Rotation around pitch axis

robot, it has 10-DOF, which makes . Therefore, a numerical solution method is used to solve the kinematics.

The mechanical structure of an articulated robot is treated as an open-loop link mechanism with bifurcation points[15]. The inverse kinematics of the 3-US parallel link by numerical solution was described in the previous paper[12]. In this paper, a kinematic model was constructed by considering this humanoid robot to be composed of one trunk and three branches as shown in Fig. 11.

In the figure, $\hat{l}_{ij}$ represents the j-th link vector at the reference position of the i-th branch, and $\hat{s}_{ij}$ denotes the j-th joint axis vector of the i-th branch. When $i = 0$, it means the trunk indicated by the black line in Fig. 11, which is one of the chains of 3-US parallel link. The other two chains of 3-US parallel link are indicated by the red and green lines ($i = 1, 2$). When $i = 3$, it means the arm indicated by the yellow line.

Inverse kinematics as a humanoid robot can be solved numerically so that the bifurcation point and the tips of the three branches are in given positions and orientations. The positions and orientations of branches 1 and 2 are set on the base plate. The position and orientation of branch 3 was set as the target position and orientation of the arm. The branching point posture was given low priority, and the branch (i = 1, 2, 3) tip position and posture were given

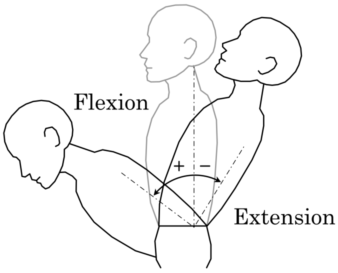

Fig. 7. Roll range of motion of waist (flexion/extension)

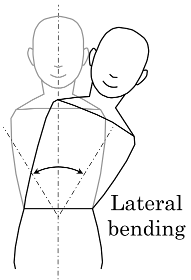

Fig. 8. Pitch range of motion of waist (lateral bending)

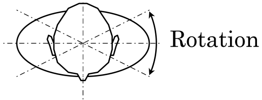

Fig. 9. Yaw range of motion of waist (rotation)

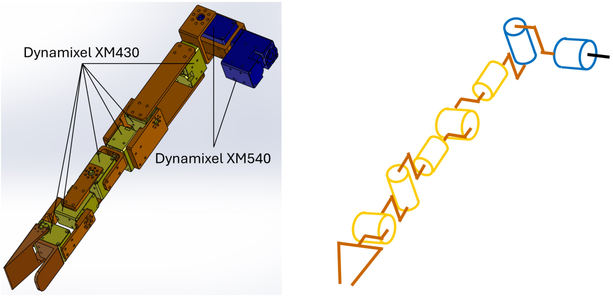

Fig. 10. 7-DOF serial link manipulator with 1 servo for end effector

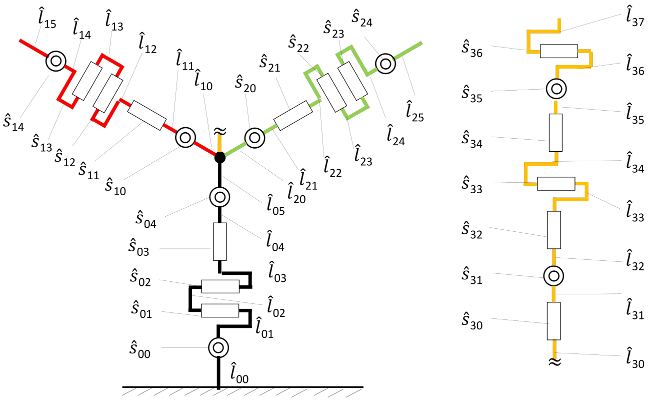

Fig. 11. Kinematics model of upper-body humanoid robot (left: waist, right: arm which is connected to the waist)

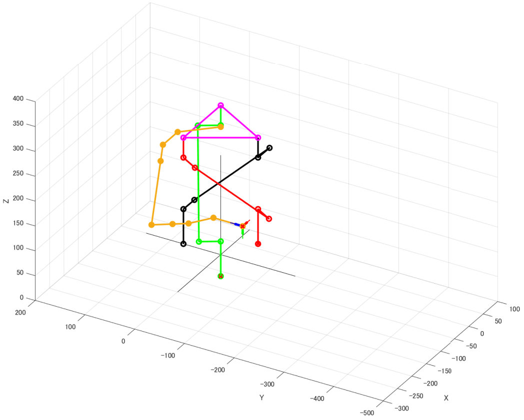

Fig. 12. Simulation (the target position/posture is within the reach of the right arm)

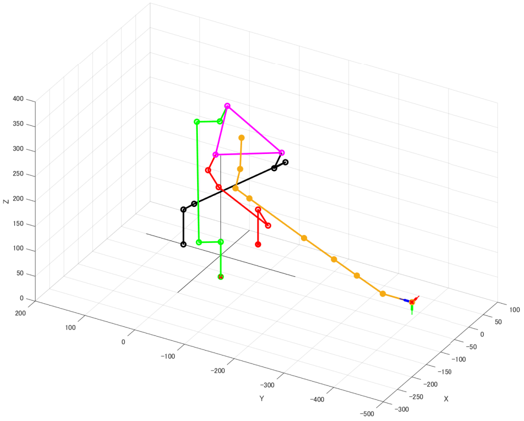

Fig. 13. Simulation (the target position/posture is beyond the reach of the right arm)

high priority [16]. Examples of numerical solution simulation results are shown in Figs. 12 and 13. The black, red, and green lines indicate the 3-US parallel link mechanism (the waist), and the yellow line indicates the 7-DOF serial link arm robot (the right arm).

As shown in Fig. 12, when the target position/posture is within the reach of the right arm, the waist does not move from the original position/posture and only the arm moves like a human. On the other hand, as shown in Fig. 13, if the target position/posture is beyond the reach of the arm, the arm can reach the target position/posture by moving the waist as well.

IV. MOTION PERFORMANCE

In this section, the humanoid was controlled with a joystick or numerical inputs to verify that the developed humanoid can reproduce human motions. The target position/posture of the robot's end effector was given by a 3-DOF joystick (TCA Sidestick Airbus Edition) with extra buttons or numerical inputs from CSV. The inverse kinematics was solved numerically from the target position/posture to obtain the required motor angles as described in the previous section. The obtained angles were sent via serial communication to the microcontroller, Robotis OpenCM9.04, to move the servo motors.

The operator controlled only the end effector of the robot with joystick or specified position and posture to perform the pick and place task of a ping pong ball. Figure 14 shows the process of the task of moving a ping pong ball from the left table to the right table in the grasped state. As can be seen in the figure, the operator specifies only the robot's end effector position and posture, but the robot moves its arm and waist in a coordinated manner to accomplish the task.

V. CONCLUSION

In this paper, we developed an upper-body humanoid robot with a right arm using a 3-US parallel link mechanism with three degrees of freedom in posture and a 7-DOF serial link arm robot. In the future, the left arm will be added and we will study the stiffness and repeatability of the entire humanoid robot.

ACKNOWLEDGEMENT

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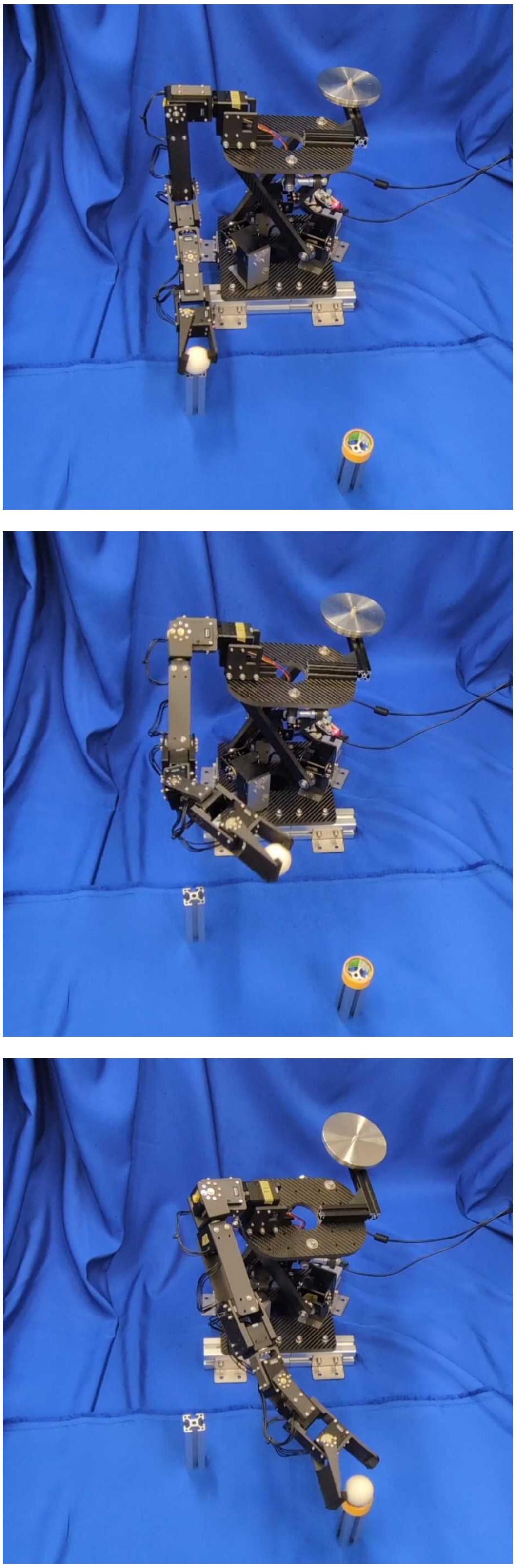

Fig. 14. Pick and place of a ping pong ball

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