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Multi-Fingered Robotic Hand Employing Strings Transmission Named "Twist Drive"

Takashi Sonoda and Ivan Godler

Abstract— **A goal of our research is to produce a light-weight, low-cost five fingered robotic hand that has similar degrees of freedom as a human hand. The joints in the fingers of the developed robotic hand are powered by a newly proposed strings transmission named "Twist Drive". The transmission converts torque into a pulling force by using a pair of strings that twist on each other. The basic characteristics of the transmission are given in the paper. A robotic hand prototype with 18 joints of which 14 are independently powered by Twist Drives was produced. The size of the hand is equal to the size of an adult human's hand and its weight including the power circuits is approximately 800 grams. The mechanical and the control systems of the hand are presented in the paper.**

I. INTRODUCTION

The ultimate goal of robotic hands research is to produce a dexterous hand that would be able to skillfully handle objects like the humans do. A need for universally useful hands attached to robotic arms is becoming apparent in the industry where shortening of production cycles and a need to timely match various requirements is calling for dexterous robotic hands that could cope with various tasks. This is even more evident in non-industrial robotics applications, where the environment is highly unstructured and dealing with various objects and tasks becomes inevitable.

A multi-fingered robotic hand that resembles a human's hand can without any special attachments handle tools that are normally used by humans and can thus help humans in performing various tasks. The costs of human training and the costs of investment into various types of end-effectors can be thus reduced, also use in the space and other extreme environments to perform tasks instead of humans becomes possible. For these reasons, expectations for the robots to be helpful to humans are linked with the development of multi-fingered robotic hands as being the most general type of end-effectors.

A human hand is able to dexterously perform pinch, grasp, and other types of objects handling by using five fingers. Each finger has multiple joints, and the whole kinematic model of a human hand has 20 or more degrees-of-freedom (DOF). The distinctive feature of a human hand is an opposable thumb which is able to 'face' the other four fingers and thus makes pinching and grasping of the objects possible. The characteristics of a human hand are to various degrees imitated by numerous developed robotic hands, e.g. Stanford-JPL Hand [1], Utah-MIT Hand [2], Omni-Hand [3], Shadow Hand [4], DLR-HIT Hand [5], HRP Hand [6], Gifu Hand [7], etc. Early multi fingered robotic hands were driven by tendon mechanisms and motors positioned outside of the hand. However, due to reduced size and increased output power of the electrical motors it is recently possible to mount the motors into the hand itself.

Disadvantages of motors and gears used to directly power the joints of a robotic hand can be summarized as lack of a free-state of the joints, high costs, and large weight. However, in the case of tendon driven joints, it is possible to relax the pulling force of a tendon and thus generate a free state (zero impedance) in a joint, so that the finger can easily be moved by an external force. This kind of zero impedance is important from a safety point of view, because it reduces impact forces in the case of collision when the joints are in a free state. Zero impedance is difficult to achieve with geared motors in the joints, thus we propose to use a new type of strings transmission.

In this paper we present a transmission system for robotic hand in which strings are used to generate a pulling force. Its functionality is similar to a tendon transmission in a sense that only a pulling force is generated, which can be instantaneously reduced to zero, so that the joint can be set to a free state in any position. The pulling force and the motion of a joint are generated by twisting pair of strings, therefore, the mechanism is named "Twist Drive". A relation between the input torque and the output pulling force of a Twist Drive is moderately nonlinear, however, the benefits of a simple structure, small-size, light-weight, low-cost, and quiet operation are appealing for the use in robotics.

The purpose of this paper is to describe characteristics of a developed five-fingered robotic hand prototype and present a control system of the whole hand. A video presentation of the developed prototype robotic hand is attached.

The paper is organized as follows. In section II we explain the structure and a principle of operation of Twist Drive, in section III we present the developed five-fingered robotic hand prototype, its mechanical, electrical, and control systems. Concluding remarks and future works are given in section IV.

II. TWIST DRIVE

A. Actuating Method

To achieve a tendon-like functioning and simultaneously convert a motor torque into a sufficiently high pulling force without using any gear reducers, we propose a mechanism

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T. Sonoda is with Fukuoka Industry, Science & Technology Foundation, Fukuoka, 810-0001, Japan. sonoda@lab-ist.jp

I. Godler is with the Department of Information and Media Engineering, University of Kitakyushu, Kitakyushu, 808-0135, Japan. godler@env.kitakyu-u.ac.jp

called Twist Drive. Two strings are with one end attached to an output shaft of an electrical motor and with the other end to a driven object as shown in Fig. 1.

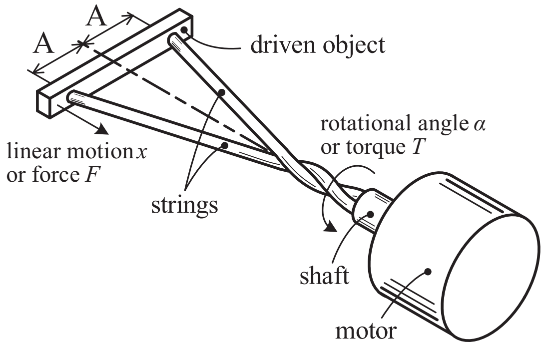

Fig. 1. Twist Drive actuation principle

When the motor's shaft is rotated for an angle α, or when the motor applies a torque T on the strings, the two strings twist on each other and in this way transform the rotation α into a linear motion x and/or the torque T into a pulling force F.

To build a kinematic model of the actuation we assume that the strings have constant length L and constant circular cross-section S with a radius R, in other words, we assume non-stretchable strings. In practice the strings are stretchable, but by using advanced fibers (e.g. para-aramid etc.), the stiffness in the longitudinal direction of the strings can be kept very high while the resistance in twist and bend directions is negligible.

A technological problem in the use of Twist Drive is a durability of the strings. Repetitive bending and twisting of the strings causes wear of the strings, and after a certain number of repetitions, which is dependent on the applied external load, the strings tear. From testing various commercially available materials we found out that recently the most durable are threads made of ultra-high-molecular-weight-polyethylene (UHMWPE). At a load in the range of about 10% of the thread's tensile strength, we achieved up to 200,000 repetitions of motions over the whole motion range of a Twist Drive.

B. Modeling and Transmission Characteristics

For a design, control, and simulation purposes we need a mathematical model of the Twist Drive's transmission characteristics. From three dimensional geometry of the strings and from unwound planar geometry of one string as shown in Fig. 2, we can obtain the following relation between the rotational angle α and the linear motion x:

$$x = \sqrt{L^2 - A^2} - \sqrt{L^2 - (A + R\alpha)^2}\,. \tag{1}$$

Note that a parameter A is the half distance between the attachment points of the strings on a driven object (see Fig. 1). A relation between the rotational speed $\dot{\alpha}$ and the linear speed $\dot{x}$ is obtained by the time derivative of (1) as

$$\dot{x} = \frac{R(A + R\alpha)}{\sqrt{L^2 - (A + R\alpha)^2}}\dot{\alpha} = \frac{R}{\tan\beta}\dot{\alpha}\,. \tag{2}$$

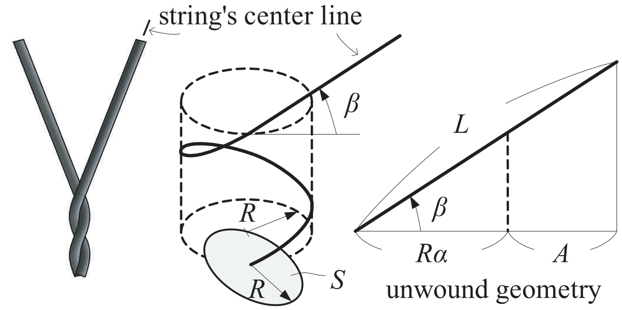

Fig. 2. Geometry of Twist Drive strings

Similarly, a relation between the torque T and the pulling force F can be obtained from energy conversation law or from force balance equations, and by assuming 100% mechanical efficiency, i.e. neglecting the friction we get

$$\frac{F}{T} = \frac{\sqrt{L^2 - (A + R\alpha)^2}}{R(A + R\alpha)} = \frac{\tan\beta}{R}\,. \tag{3}$$

The above equations describe a so called 'gear ratio' of the Twist Drive ($\tan\beta/R$), which varies over the motion range as a nonlinear function of the string's inclination angle β. An example of transmission characteristic obtained with parameters $L = 25\,\text{mm}$, $R = 0.2\,\text{mm}$, and $A = 7\,\text{mm}$, which are actually the parameters that are used in our robotic hand prototype, is shown in Fig. 3.

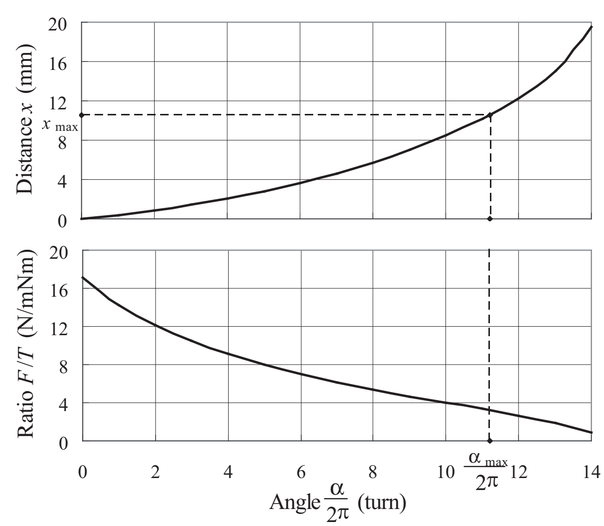

Fig. 3. Example of transmission characteristics of Twist Drive

The obtained transmission characteristic is nonlinear, but the nonlinearity is moderate, especially in the range up to $\alpha_{\max}$, which is considered to be the motion range of the device.

The end of a motion range is defined as a state where the strings are twisted into a compact helical shape with pitch $4R$ as shown in Fig. 4.

The calculations from an unwound geometry give the

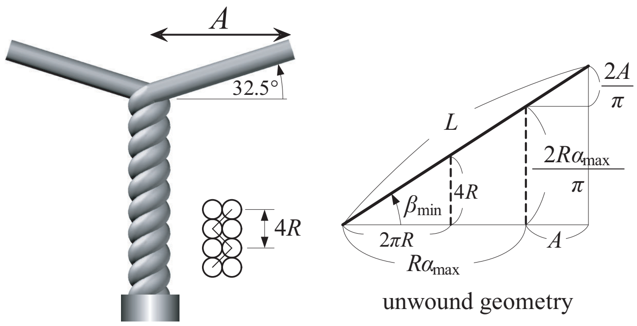

Fig. 4. Motion range of Twist Drive

TABLE I
SPECIFICATIONS OF BRUSHLESS DC MOTORS

Item	Value Φ17motor (Φ12motor) nominal	maximum	Unit
Supply voltage	24 (12)		V
Torque	10 (6)	30 (10)	mNm
Current	0.38 (0.86)	1.1 (1.4)	A
Speed	3500 (8000)		rpm
Num. of poles	4 (4)		

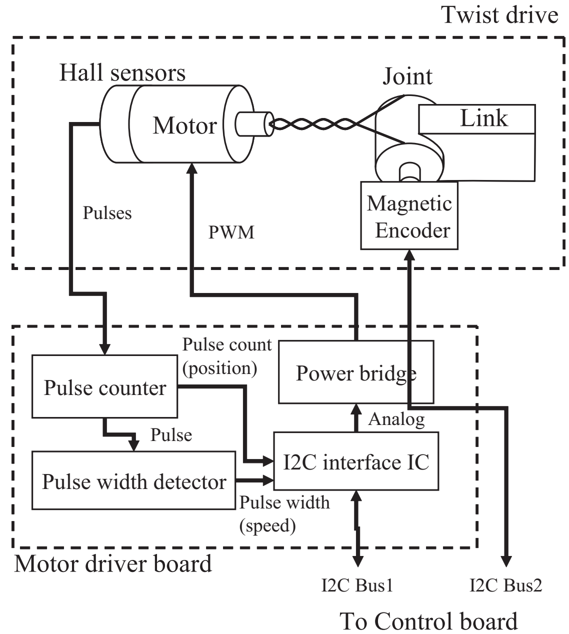

Fig. 5. Joint control system with Twist Drive

following formulae:

$$\alpha_{\max} = \frac{\pi L - A\sqrt{\pi^2+4}}{R\sqrt{\pi^2+4}} \quad (4)$$

$$x_{\max} = \sqrt{L^2 - A^2} - \frac{2L}{\sqrt{\pi^2+4}} \quad (5)$$

$$\beta_{\min} = \tan^{-1}\frac{2}{\pi} \approx 32.5^\circ \quad (6)$$

The above derived formuale define the motion range, nevertheless, the strings can be still further twisted by applying sufficient torque, but generated pulling force above this range is very low as can be confirmed from the ratio F/T in Fig. 3.

III. ROBOTIC HAND PROTOTYPE EMPLOYING TWIST DRIVE

A. Structure of Robotic Hand Prototype

1) Joint Mechanism: As it was already reported in [8], the authors developed a robotic finger with the DOF that resemble a human finger. A block diagram in Fig. 5 describes a control system of a single joint of a finger with employed Twist Drive. Note that the strings are with one end attached to a shaft of a motor and with the other end directly to the link of a finger. In this way the available space in the finger is efficiently used, while the structure of a finger is simple, because there are no pulleys or other intermediate transmission parts. The difference between pulley and direct fixture was discussed in [8], where it is shown that selection of fixture position influences the torque characteristic over the motion range of a joint. Also, note that because the strings can only pull and cannot push on the link, a spring (not shown in Fig. 5) is employed in each joint for returning motion.

The joint's flexion is powered by Twist Drive with a brushless DC motor having data given in Table I. The data in Table I are given for a motor $\Phi 17\,\mathrm{mm}$, which is used for flexion, and in parentheses for a motor $\Phi 12\,\mathrm{mm}$, which is a smaller motor used for abduction of the index, ring and small finger, to spread the fingers of the hand (refer to attached video).

Each motor is equipped with three digital Hall sensors for commutation. To save the space, we use the outputs of these sensors to detect the motor's angular position. The highest possible resolution of motor's position is in this arrangement of our prototype 12 pulses/revolution. Actual position of the motor is managed by a hardware pulse counter, which is a part of a custom made motor driver board (see Fig. 5). The motors in the case of Twist Drive rotate for maximum 11 to 12 rotations, therefore, an 8 bit up-down pulse counter is sufficient.

The motor driver board additionally has a pulse width detector, which is used to detect the motor's rotational speed by measuring the width of the pulses that are coming from the Hall sensors. The detector is a 12 bit up counter with a synchronized hardware latch and reset functions, and is continually counting the pulses of a 12 kHz clock pulse generator circuit, which is also a part of the motor driver board.

An I2C interface IC is used to communicate the motor position (the value in a 8 bit counter), the motor speed (the latched value in a 12 bit counter) to a control board, and to transmit a PWM voltage command from the control board to a power bridge. A 3 phase power bridge IC with an analog input is used, therefore, a digital command received from a control board is first converted into an analog voltage by a simple 8 bit R-2R ladder D/A converter circuit (not shown in Fig. 5).

Different from a geared motor, a Twist Drive does not

TABLE II

SPECIFICATIONS OF CONTROL BOARD

Item	Value
Dimensions	45 x 25 mm
MPU	dsPIC33FJ256GP506
I2C	2 channel
CAN	1 channel
RS232	1 channel
General I/O	8 channel
A/D	2 channel

provide constant and linear relation between the motor angle and the joint angle, therefore, joint angle sensors are assembled into the joints' mechanisms. To avoid the need for initializations, an absolute 12 bit magnetic encoder AS5046 product of Austriamicrosystems AG was used. The magnetic encoder has a built-in I2C interface, which is again used for the communication with the control board.

2) Finger and Joint Control Systems: To achieve modularity and sufficient computational power of the servo control level, we use separate control boards to control all the joints of each finger separately. A summary of specifications of a prototype control board is given in Table II. The control board is based on a MPU dsPIC33FJ256GP506 with 2 channels I2C bus interface, 1 channel CAN bus interface, and 1 channel RS232 interface. It also has 8 channels of general I/Os and 2 channels of A/D converters, which are presently not used.

Channel 1 of the two I2C bus channels is used to communicate with the motor driver boards of a finger and channel 2 is used to communicate with the magnetic encoders in the joints. The software servo-control runs on the PIC MPU with a sampling frequency of 1 kHz, and has the following three different modes of operation:

The first mode is a simple open loop PWM command mode, which is used to supply a command voltage to the motor in a simple open loop fashion. This mode can be used as an open loop force control, for simple grasping tasks.

The second mode is a position proportional (P) and a speed proportional-integral (PI) servo control of a motor. This mode is used for a coarse positioning of fingers, and for untwisting the strings to achieve a joint's free state. Extension of the fingers is done in this mode by untwisting the strings and letting the force of installed spring to extend the finger. A block diagram of the motor position control with speed minor control loop is shown in Fig. 6.

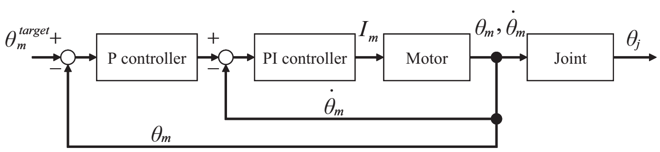

Fig. 6. Motor position and speed control

The third mode of servo control is more complex and is used for precise positioning of the fingers. Low resolution of the motor angle sensing and nonlinear transmission characteristic of the Twist Drive require a closed loop position control of the joint by using a position feedback from the joint itself. A 12 bit absolute magnetic encoder in the joint gives a resolution of $0.088°$ in the joint, which is sufficient for most applications. A block diagram of the joint position control is shown in Fig. 7. Note that this control mode itself has two different operation modes and one 'safety valve'.

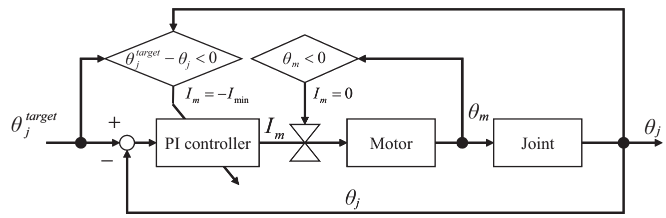

Fig. 7. Joint position control

In the case when the joint angle target θ_j^{target} is larger than (above) the actual joint angle θ_j, the motor is operated by the PI position control in a closed loop servo mode with a feedback from the joint angle sensor. In this case the Twist Drive pulls on the link of a finger to rotate the joint towards the target position. In the case when target position is smaller than (below) the actual joint's position, the Twist Drive cannot push on the link to rotate the joint towards the target position, therefore, a small negative voltage $-V_{\min}$ is supplied to the motor to untwist the strings and let the spring move the joint towards the target position. However, if for example the finger is artificially held by an external constraint to a position that is above the targeted one, the motor would rotate past its initial position and on the negative side again start to twist the strings into opposite direction, which would again pull the link of a finger. To protect the joint position control from this kind of a 'runaway' control, a 'safety valve' is added to stop the motor as soon as the crossing of initial position into a negative direction ($\theta_m < 0$) is detected, regardless of the actual or target joint position. Throughout the experiments with the developed prototype fingers and with the hand we found that this simple dealing with the nonlinearities of a Twist Drive is quite effective and sufficiently simple for position control of the fingers.

3) Finger Mechanism: To reduce the number of needed motors, the top two DOF in a finger are coupled with each other by a coupling string of a fixed length. The coupling string with joints and links forms a four bar linkage mechanism, of which one link is a string. This configuration allows for the DIP joint to freely move in the flexion direction under an external force, and in this way similar to the other joints that are powered with Twist Drives, contributes to safety in an eventual collision with the environment.

A drawing of the designed prototype finger's PIP and DIP joints is shown in Fig. 8. A simple structure comprised of a Twist Drive pulling strings, a coupling string, and a spring for extension is depicted. The coupling ratio of PIP and DIP joint angles is set to approximately 2, which is at the upper range of what is measured for human fingers [9]. In a four bar linkage, the coupling ratio of the joint angles is not constant, which needs to be further studied in our future work.

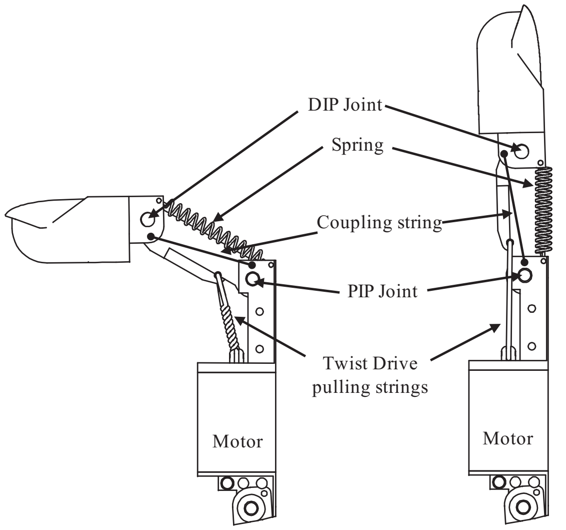

Fig. 8. Structure of finger's PIP and DIP joints with Twist Drive and string coupling

4) Hand Mechanism and Hand Control System: A CAD drawing of the developed five-fingered robotic hand prototype employing Twist Drive, and a photo to compare its size to an adult human's hand size are shown in Figs. 9 and 10 respectively. The main dimensions and other significant

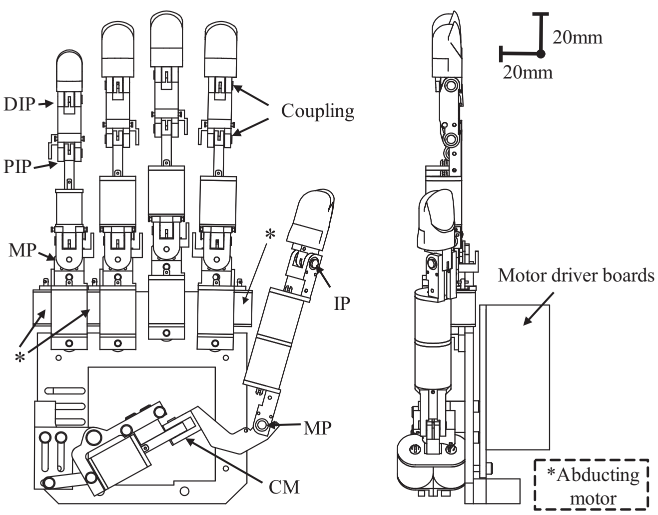

Fig. 9. Drawing of prototype robotic hand

parameters of the prototype hand are listed in Table III. Note that the total weight of the prototype hand including the motor driver boards is approximately 800 grams, which is quite low considering that the hand has 18 joints of which 14 are independently powered. The motion ranges of joints are shown in Table IV. Note that MP joints of all fingers except the one of a middle finger have 2 DOF, namely flexion and abduction.

All joints except the thumb's CM joint are powered by Twist Drives in one direction and by springs in opposite direction. Only the thumb's CM joint is powered by two Twist Drives in a 'pull-pull' fashion, to achieve active force

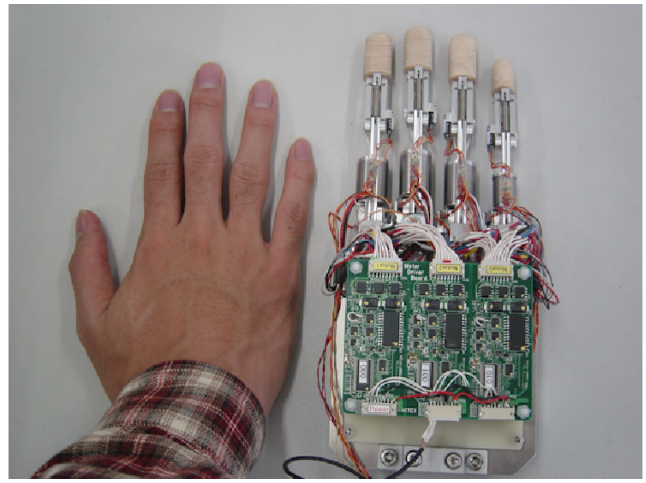

Fig. 10. Prototype robotic hand in comparison to adult human hand

TABLE III

SPECIFICATIONS OF ROBOTIC HAND PROTOTYPE

Item	Value
Dimensions	238 x 116 x 72 mm
Weight	approx. 800 g
DOF	18 of which 14 independent
Max. grasp force	10 N per finger
Motors	Brushless DC x 15
Sensors	Joint angle (12 bit) x 14

control in both directions. The maximum grasp force of one finger is about 10 N near to the extended joints and decreases with the joints flexion. Calculated and measured characteristics are in agreement and will be reported at some other occasion.

The control system of a prototype hand is composed of 15 motor driver boards, one for each motor, and five control boards, one for each finger. The communication and function of the motor control part was explained in subsection III-A. The control boards (CBs) communicate with each other and with a host control board (host CB) by a CAN bus as shown in Fig. 11. The host CB also communicates with a PC (personal computer) by a RS232 interface with a function to transmit the data from the hand's sensors to the PC and to receive control commands from PC, including the selection of a control mode. High level control and complex calculations including inverse kinematics etc. will be performed on PC, while the low level servo control is handled by the control boards. The host CB is used for communications only.

The presented configuration at the time of the paper submission is used only for position control of joints and

TABLE IV

JOINTS' MOTION RANGE

Finger	Joint and its motion range
Thumb	CM 85°, MP 65°, IP 78°
Index, Ring, Little	MP flex. 80°, MP abd. 30°, PIP 100°, DIP 50°
Middle	MP flex. 80°, MP abd. 0°, PIP 100°, DIP 50°

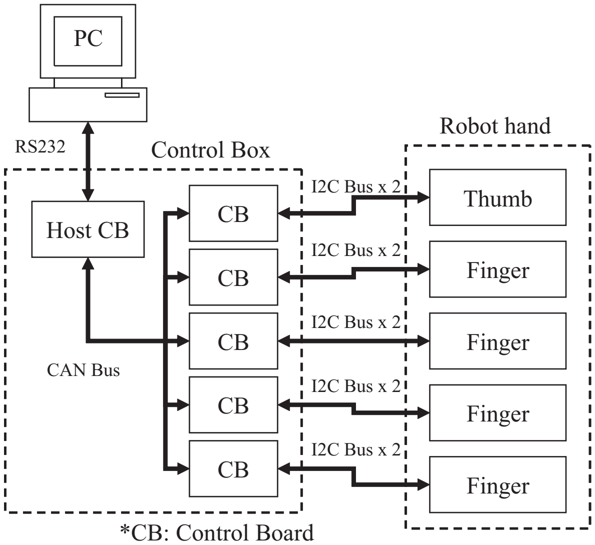

Fig. 11. Robotic hand's control system

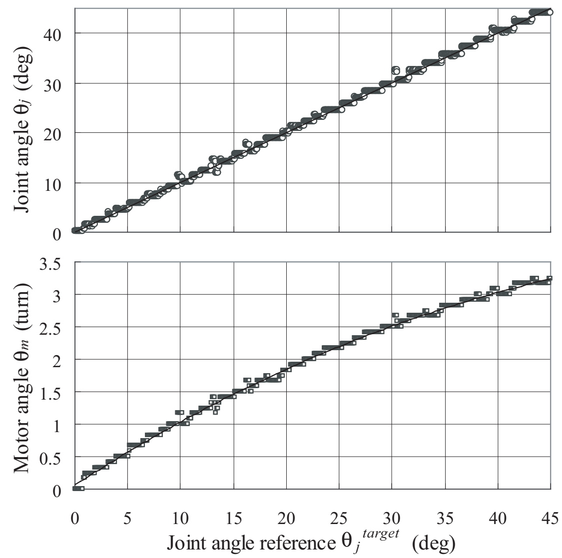

Fig. 12. Joint positioning control experimental data

motors, and for voltage control of the motors in simple grasping tasks, but in the future the system will be equipped with force sensors to produce force feedback control.

B. Positioning Control Experiment

To verify the possibilities of a Twist Drive for robot's joint control, a simple closed loop positioning control experiment was performed. A graph of joint's position θ_j and motor's position θ_m plotted against the joint position command θ_j^{target} is shown in Fig. 12.

Note that the joint position linearly follows the joint position command while the motor position is due to Twist Drive's characteristics nonlinearly related to the command. A stepping-like resolution was caused by a low resolution of motor position sensing and amplified by a high cogging torque of a brushless DC motor which was customarily designed for high output torque. Commutation quality should be improved in the future to achieve higher positioning resolution and more smooth operation. A demo video and other materials can be accessed from [10].

IV. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

A newly proposed strings transmission called Twist Drive was employed to power the joints of a five fingered robotic hand. The proposed transmission mechanism is beneficial due to light-weight, low-cost possibility to build a robotic hand that has 18 joints. The basic characteristics of a Twist Drive transmission and control systems of the developed robotic hand prototype were presented in the paper. The nonlinear characteristic of the Twist Drive was effectively controlled by using three modes of control. The developed prototype exhibited stable positioning performance by using position feedback from the joints' sensors. A simple open loop force control to demonstrate pinching and grasping tasks is presented in attached video.

B. Future Works

DC motors were used in the developed prototype used brushless to achieve high torque and consequently high grasping force. However, a cogging torque on the motor shaft was quite significant and thus it obstructed smooth motion of the joints. In the future we need to improve smoothness of joints' motion by upgrading commutation quality of brushless DC motor's electronics. Also, to make the robotic hand more useful, we need to attach force sensors to the fingers and to the palm, and develop a force feedback control strategy for dexterous tasks.

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