Abstract—This paper proposes a linkage-driven manipulator having linear ultrasonic motors inside of an elongated shaft. The manipulator can be divided into a driving rod module and wrist joint module. The driving rod module consists of several ultrasonic motors and driving rods. Flexible leaf springs between the ultrasonic motors and the driving rods enable synchronized motion of the driving rod by compensating mechanical clearance and different characteristics of ultrasonic motors. Two driving rods operate 2-DOF wrist module by linear motion. The wrist joint module is composed by two non-closing rotation joints, serially connected sliders and intermediate linkages, and designed to rotate from +60° to -60° in yaw and pitch directions respectively. The wrist parameters are determined by parametric studies of the motion range and torque characteristic, and the effect of the flexible leaf spring is studied by simulation. Experiments are performed in order to evaluate the velocity-force characteristic of the rod module.

I. INTRODUCTION

Minimally Invasive Surgery (MIS) established in the 1980s is the operation that is less invasive than open surgery by using laparoscopic devices through small incisions and manipulation of instrument with indirect observation of operation area through an endoscope. This resulted in a reduction of trauma to tissues, decreased pain and shorter recovery time. It is also cosmetically beneficial that only smaller visible scar remains on the body from the operation. MIS procedure is clearly advantageous in terms of patient outcomes. During the procedure, surgeons must use tools to interact with tissue rather than manipulate it directly with their hands. And the endpoint of tool moves in the opposite direction to the surgeon's hands due to the pivot point, thus direct hand-eye coordination is lost [1] and the motion scaling depends on the depth of instrument insertion. This awkwardness of opposite motion can be more problematic in delicate operations such as suturing.

Robotic technology can ameliorate the difficulties of the MIS procedures. Surgeons can regain virtually direct observation of the operation site by robotic system which includes delicately miniaturized mechanism, robotic arm, master console and tele-operation technology. With the aid of robotic systems, the instruments are not directly manipulated by surgeon anymore. Instead they are remotely manipulated by the surgeon who operates master devices in a console while the instruments are following the command taken in the master device. With appropriate control algorithms the reverse motion can be avoided and the direct hand eye coordination is regained. The robotic systems can transmit the downscaled motion of surgeon to surgical instrument so the motion of instrument becomes more accurate than in open surgery. In addition, some kind of control algorithm can remove the possible hand tremor and make surgery safer. The da Vinci® System from Intuitive Surgical Inc. is an example of the commercialized MIS robotic surgery system and provides superior visualization, enhanced dexterity and greater precision to surgeons [2].

Many other robotic systems have been developed for MIS. These systems include a bimanual robotic system with two arm having six degrees of freedom for single-port laparoscopy[3], a Insertable Robotic Effectors Platform(IREP) having compact deployable mechanical structure and stereo vision[4][5], Highly Articulated Robotic Probe[6] and instruments with force sensing capability[7][8]. Some works are focused on embedding the actuators inside of the instrument for small size. An articulated universal joint based flexible access robot has been successfully developed and 7 joints of the robot is controlled independently [9] and a high dexterity modular instrument is proposed for coronary artery bypass grafting surgery[10].

Actuated instruments with additional DOFs (degrees of freedoms) facilitate dexterity inside the human body and reach every point in the surgery site with arbitrary orientation. In conventional system, actuators to operate the instrument are installed in the robotic arm and transmit complex motions and proper force to surgical instruments using cables, since the cable easily bends and changes the direction of force applied to it. However backlash of the system increases with increasing length of cable which connects actuator and wrist joint of the surgical instrument. Furthermore, the long-term operation can permanently extend the length of cable to degrade the performance of surgical robot. High tension applied to the cable can be a solution of backlash problem, but it could increase the possibility of breakage.

Alternative solution to the high tension and breakage problem can be linkage mechanisms. While the cable sustains only extension force, linkage can sustain both the compression and extension force. Thus the force acting on the instrument body and the rotation shaft can be a half of the cable-pulley system. Many researchers have tried to develop the linkage-driven surgical instruments [11][12]. One successful example is a multi-slider mechanism which has two directions of wrist motion and implements each motion with three frames and two revolute joints [13][14].

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The aim of the research is to design new robotic surgical instrument that are able to be used in the general MIS. This paper proposes an endoscopic manipulator with linkage-driven wrist joint operated by linear ultrasonic motors inside of an elongated rod shaft. The manipulator achieves compact size by the embedded actuators, reduced backlash by linkage driven structure and high wrist force by short wrist length. Several ultrasonic motors push the driving rod with synchronized motion while only one micro-motor rotates each joint of the instrument shown in [9].

II. OVERVIEW OF THE PROPOSED MANIPULATOR

Fig. 1 shows an overview of the proposed manipulator consisting of a gripper to manipulate tissues, wrist mechanism to orient and reach the surgery site, embedded ultrasonic motors for wrist motion and an actuator for gripping motion.

The design of the manipulator is aimed for compact surgical robot. All of the components are included in the rod module of the manipulator, and the robotic arm which holds the manipulator needs not to equip extra devices to drive the manipulator. Thus, the design of robotic arm can be more compact and slimmer.

The manipulator can be divided into an embedded ultrasonic motor module and wrist joint module. Ultrasonic motors which are embedded in a driving rod module drive the wrist mechanism by pushing and pulling the driving rods, and the linkages guided by serially connected sliders move pitch frame and yaw frame of the wrist module.

III. EMBEDDED ULTRASONIC MOTOR MODULE

A. Design Approach

We can consider two different approaches manipulating the wrist joint and tools of surgical manipulator. One is a remote actuation method which operates the joints and tool by remotely located actuator. This method is advantageous to transmit high force from outside to inside of the operation site, since the size of actuator is not limited and the actuation element such as cable and linkage transmits the motion and force of actuators. The other is an embedded actuation method of which actuators are inside of the manipulator body. In this method, a robotic arm holding the surgical manipulators needs not to contain actuators so that the size of the robotic arm can be reduced and the collision between the arms can as well. Moreover, the embedded actuator can independently operate the wrist module without influencing the motion of another wrist module. Thus, the manipulator could be easily designed to have multiple wrist modules which have an increased accessibility to surgical site.

We have focused on designing the embedded actuation mechanism in order to get the compactness of surgical robot and the easiness of extension to the multiple wrist modules on a single surgical manipulator. Miniaturized ultrasonic motors are good candidate for actuators of the manipulator, because they have advantages such as high power efficiency with millimeter size and no need of reduction gear. Despite the efficiency, the generated force is not enough for the wrist motion. So we integrate several ultrasonic motors for the operation of the wrist mechanism.

Fig. 2 shows connection mechanism between driving rod and ultrasonic motor. Rod module has two driving rods for two directionally independent translations. The motor housing is rigidly fixed to the mechanical base of manipulator each other. Motor axis moves back and forth, as the screw rotates on the threaded nut. Power of each ultrasonic motor has concentrated on the driving rod, while the motors operate synchronously by the same motion command.

![Fig. 2. Connection between driving rod and ultrasonic motor](image1)

To synchronize motion of the driving rod, we employ flexible leaf springs between the ultrasonic motors and the driving rod and compensate mechanical clearance and different characteristics of ultrasonic motors. The ultrasonic motor can be broken by excessive axial force unless the external force is distributed to the axis of ultrasonic motor properly by the flexible leaf spring. Thus the design of the leaf spring is one of the most important factors in the embedded ultrasonic module.

Fig.3 shows the structure of SQUIGGLE motors by New Scale Technologies. Twelve 3.4mm SQUIGGLE motors are installed and synchronized inside of rod module and operate 2 axis of wrist module independently.

The motor basically consists of a threaded nut and screw. Two-phase drive signals cause piezoelectric actuators to vibrate the nut at a fixed resonant frequency. The nut vibrates in orbital motion that causes the screw to rotate and translate with sub-micrometer precision. The screw translation is
bi-directional, and the position of the tip of the screw is precisely controlled by the driver. Speed is variable from micrometers per second to millimeters per second.

Someone can derive alternative design for compensating mechanical clearance and different characteristics of ultrasonic motors. For example, screw of SQUIGGLE motors could be connected each other rigidly or flexibly in a single screw axis in order to magnify the push-pull force, and the structure could be simple. However, it is hard for the stator to push and release the screw simultaneously because every piezo material has the different resonant frequency and phase.

The screws operated by different frequency and phase can disturb the motion of each other. Even though the orbital motion is simultaneously generated, the screw could not rotate sometimes due to the compression and extension of screw along the axial direction. Another problem is that the screw close to the wrist joint should hold high force that a single SQUIGGLE motor cannot hold. This feature can damage the motor and shows why the flexible leaf spring and the driving rod are required. Detailed parameters of the leaf spring can be determined by simulations.

B. Effect of the Leaf Spring

Leaf springs play role of synchronizing the linear motion of each ultrasonic motors. Multi-body dynamic simulation tool, ADAMS, is employed to obtain proper thickness of the leaf springs. The proposed rod module includes multiple ultrasonic motor which applies the force to the driving rod simultaneously. The power of the motor should be accumulated to the driving rod with high efficiency, and the external force applied to the driving rod should be equally distributed to the axis of the motor not to damage the motor. However the ultrasonic motors have different speed and force characteristics, so it is hard to synchronize the motion of the motors.

As mentioned before, our approach to synchronize motion is transmitting the motor force to the driving rod through the flexible leaf spring. We established a simulation model in order to simulate the synchronized motion of the motors shown in Fig. 4. Five motors are installed in between two leaf springs, so that the motors can apply the force to the driving rod by pushing the leaf spring back and forth. Each motor is fixed to the base of rod module, and operated by sinusoidal command (20mm peak to peak) with phase noise. The driving rod is guided to move linearly, and interact with the spring fixed in the ground.

In order to consider the fabrication error and phase error, motor A has 0.1 radian of phase difference and its clearance to the leaf spring is set to small value compared to the others. Thus motor A would push the driving rod first whenever the motors get command signals.

Fig. 5 shows the simulation results with hard leaf spring and the lines indicating the required force B through E are overlaid. We can find that the required force of motor A is three times higher than the force of the others. This result represents the different mechanical and driving condition can induce the irregular force distribution which could result in the breakage of the motor shaft.

Fig. 5. Force distribution of ultrasonic motor with hard leaf spring

Fig. 6. Force distribution of ultrasonic motor with flexible leaf spring

To avoid this irregularity, we modeled leaf spring as a flexible body. Even though each motor has a different shaft displacement, flexible leaf spring could compensate the irregularity of shaft displacement. In the next simulation, we replaced the leaf spring that could deflect 0.3mm under force of 2N. From beam deflection formulae, leaf spring is design to have 0.2mm thickness, 3mm width and 10mm length.

Fig. 6 shows that the irregularity of the force distribution is drastically decreased with the design of flexible leaf spring. Although the compensated force irregularity decreases with the more flexible leaf spring, the leaf spring could permanently bend under the required force if it is designed too thin.

IV. WRIST JOINT MODULE

A. Serially Connected Slider

2-DOF wrist mechanism consists of two non-closing rotational joints, serially connected sliders and intermediate linkages. While slider-crank mechanism is applied to rotate the yaw frame, the intermediate linkage guided by serially connected sliders moves pitch frame. The wrist module is designed to rotate from +60° to -60° in yaw and pitch directions respectively, considering the relationship of wrist
force, wrist orientation and mechanical interference each other. The yaw frame angle depends on only the displacement of the yaw driving rod. On the other hand, the pitch frame motion depends on displacements of the pitch driving rod and the yaw driving rod as shown in Fig.7.

\[ p + p_o = l_c \cos \rho - l_p \sin(\theta + \theta_o) \]  

(2)

From (2), we can investigate the required slider guide length. The domain of the \( \theta \) can be defined from two singular position of slider-crank mechanism as follow:

\[ -\cos^{-1}\left(\frac{l_f}{l_p + l_c}\right) < \theta + \theta_o < \frac{\pi}{2} + \sin^{-1}\left(\frac{l_c - l_f}{l_p}\right) \]  

(3)

Another important factor in designing the wrist joint is the relation between push-pull force and joint torque. By assuming the equilibrium of the vertical force acting on the connecting rod and torque around point \( C \), force-torque relation can be derived as shown in (4):

\[ \tau_c = l_p F_p (\cos(\theta + \theta_o) - \sin(\theta + \theta_o) \tan \rho) \]  

(4)

where \( \tau_c \) is torque around point \( C \), \( F_p \) is force acting on the connecting rod. From (1) to (4), we can inspect the motion range, kinematic characteristics and statically transmitted force-torque curves of the crank-slider mechanism. Fig.9 shows that the motion range of the joint mechanism increases with the increasing connecting rod length and the decreasing offset distance.

![Diagram](image_url)

**Fig. 7. Wrist joint mechanism with serially connected slider.**

**Fig. 8.** Bending procedures of the mechanism and parameters definition.

**B. Slider-crank Mechanism Design**

Fig. 8 shows the bending procedure of 1-DOF slider-crank mechanism from +60° to -60° and parameters definitions. 1-DOF bending mechanism has two frame, connection rod, slider and 3 joints. Frame 1 has a slider guiding one distal end of the connecting rod and is pivotally connected with frame 2. The connecting rod is connected with actuator by another linkage. And the sliding motion of the linkage makes the connecting rod and frame 2 rotates around point \( C \) simultaneously. Relation equation between \( \theta \) and \( \rho \) can be written from the horizontal position condition as follow:

\[ l_p \cos(\theta + \theta_o) = l_f + l_c \sin \rho \].  

(1)

where \( l_p \) is the distance between point \( C \) and point \( A \), \( l_f \) is the offset distance of the slider guide, \( l_c \) the length of connecting rod, \( \theta \) is the angle of the frame2, and \( \rho \) is the angle of the connecting rod as shown in Fig. 8. And the vertical position of point \( R \) can be written as follow:

\[ p + p_o = l_c \cos \rho - l_p \sin(\theta + \theta_o) \]  

(2)

We selected several combinations of design parameters with which the mechanism can bend over the range of 200° from Fig.9, and investigated the transmitted torque characteristics with the constant push-pull linkage force. Fig. 10 shows that there is one local minimum and maximum near 100° and -20° respectively. The difference between maximum and minimum increases as the slider guide approaches the center line (decreasing \( l_f/l_p \)). Since the large variation of torque prevents the smooth motion of wrist joint, it is desirable to design the slider guide as far as possible from the center line of the frame 1. Even though we have tried to design \( l_f/l_p \) as high as possible, design parameters \( (l_c/l_p, l_f/l_p) \) are determined to \((1.2, 0.5)\) because the thickness of the rod is 2.5mm and the slide guide needs space for structure to
support the normal force. And the diameter of the instrument is 15mm.

V. EXPERIMENT

A. Fabrication

The proposed endoscopic manipulator is designed and fabricated according to the design guideline as shown in Fig. 11. The gripper is actuated by on cable counteracted by a spring, and a force sensor which senses the force applied to the gripper is attached to the wrist. In order to control the wrist motion, two linear magnetic encoders are in the distal end of the endoscopic manipulator. The desired position control is possible by the relational equations derived from the kinematics.

B. Performance Evaluation

Fig. 12 shows the experiment setup for force measurement. The ultrasonic motors are operated by motor control boards and transmit the force to the driving rod through the leaf spring. Rod module and push-pull gauge are fixed to the base plate, and the interaction force is measured 30 times by the gauge.

We measured the stall force of the rod as the number of the motor is increased from 1 to 5. It is shown that the average and the standard deviation of stall force proportionally increases with the increasing motor number. The circles and I-shaped mark indicate mean values and standard deviation of 30 times stall force experiments respectively. With 5 ultrasonic motor, 24N of the stall force is obtained (See Fig. 13).

Fig. 14 shows experimental setup for the velocity-force characteristics evaluations of the rod modules. A position sensing module is mounted on the rear of the manipulator in order to measure the speed of the driving rod. And we have confirmed that two magnetic encoders can measure the position of two rods without magnetic interferences each others. The constant force is applied to the driving rod axially by connecting the mass with the known weight to the distal end of the driving rod. While the ultrasonic motor and the driving rod move linearly, the displacement of the driving rods can be measured by the position sensor module. We estimate the velocity of the driving rod by differentiating the displacement under the constant load. By changing the weight connected to the driving rod, we have adjusted the force acting on the driving rod.

Fig. 13. Stall force of the rod module

Fig. 15 shows the velocity-force characteristics curves obtained by iterative measurements of the driving rod module velocity. The velocity of the driving rod slows down with the increasing load, while the force that the rod supports increases as the number of motors increases. And it is shown that the driving rod can linearly move with velocity of 4.5mm/s and 7.6mm/s under the load of 10N when five and six motors are equipped respectively. And the gripper can manipulate the soft tissues with 2-3N of force when 10N of force applied to the driving rods.
displacement of motor was compensated by the flexible leaf spring between the motor and the driving rod. Other effects of the leaf spring are shown in the feedback control experiments. The motion discontinuity and the steady-state error have been reduced by the alleviated sudden movement and impact of the motor shaft.

Two driving rods operate 2-DOF wrist module. The wrist joint module is composed by two non-closing rotation joints, serially connected sliders and intermediate linkages, and designed to rotate from +60° to -60° in yaw and pitch directions respectively. The experimental results show that its stall force is over 24N with 5 ultrasonic motors.

In the future work, we will focus on the control of the wrist joint and the integration with slave robots and master devices.

REFERENCES


VI. CONCLUSION

In this paper, we proposed a linkage-driven endoscopic manipulator having linear ultrasonic motors inside of an elongated shaft. The compact size of surgical robot is possible to implement by the embedded actuation, while the backlash can be reduced by linkage-driven actuation. The irregular