Remote minimally invasive surgical system

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Minimally invasive surgical system with augmented force presentation capability

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Problems to be solved 1

- **In the bending type forceps using the cable, it is often cut during the surgical operation.**

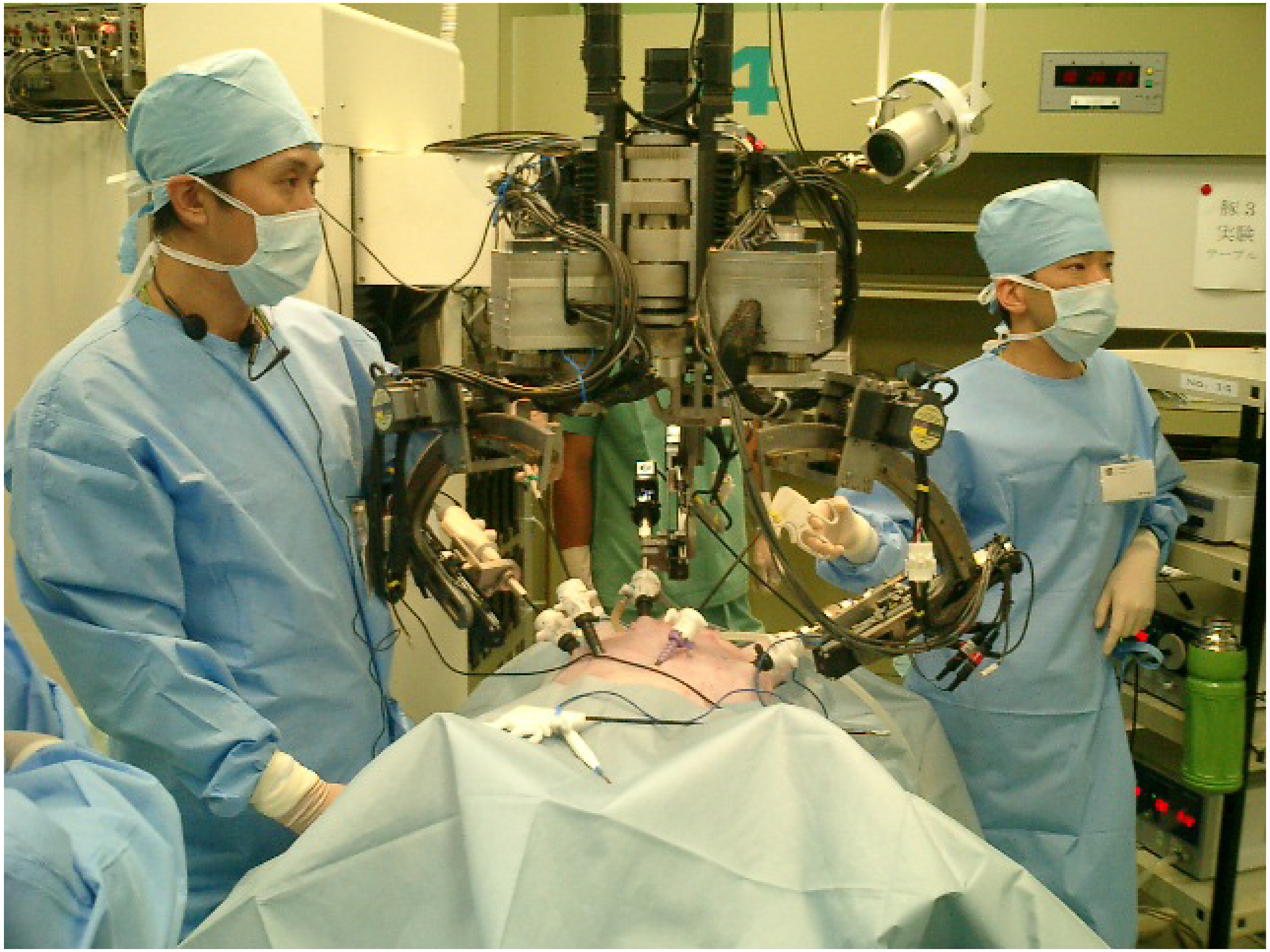
- **Link driven type multiple d.o.f. forceps has been developed.**

Problems to be solved 2

- **The force cannot be monitored by the operator while handling soft tissue because the reduction ratio is too high.**

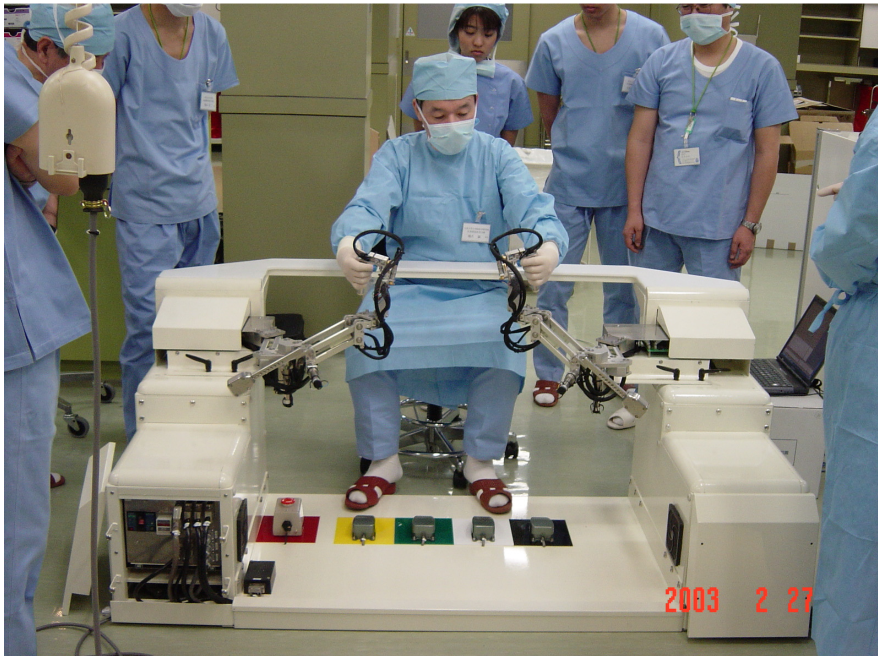
- **Force sensing method for the link driven type multiple d.o.f. forceps was developed.**
- **A method for augmenting the presentation of the measured force to the operator is proposed.**

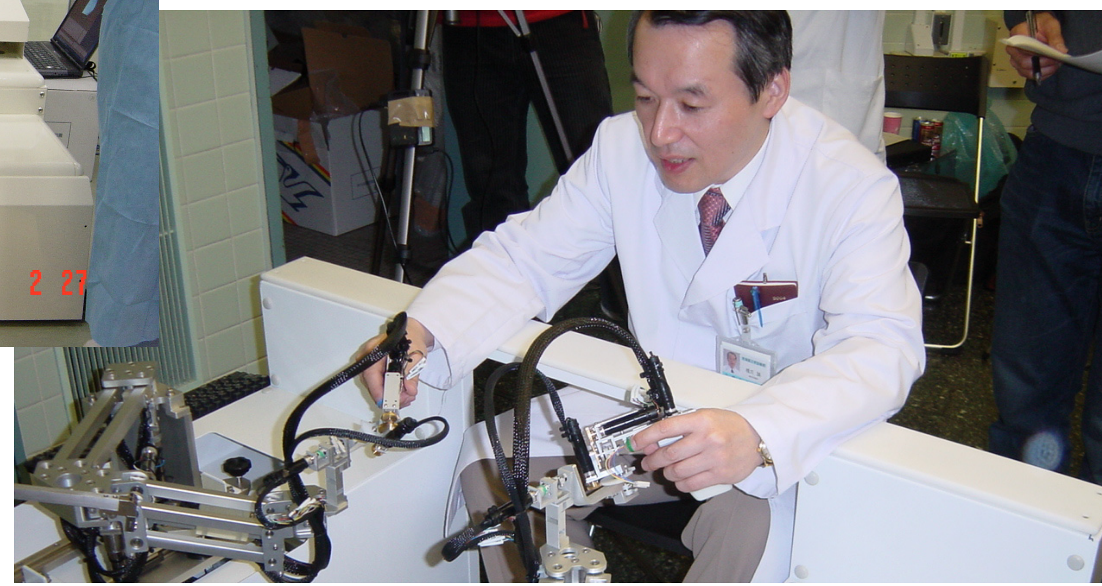
Slave manipulators with 3 arms



The left and right arms hold the bending forceps.
The center arm holds an endoscope.

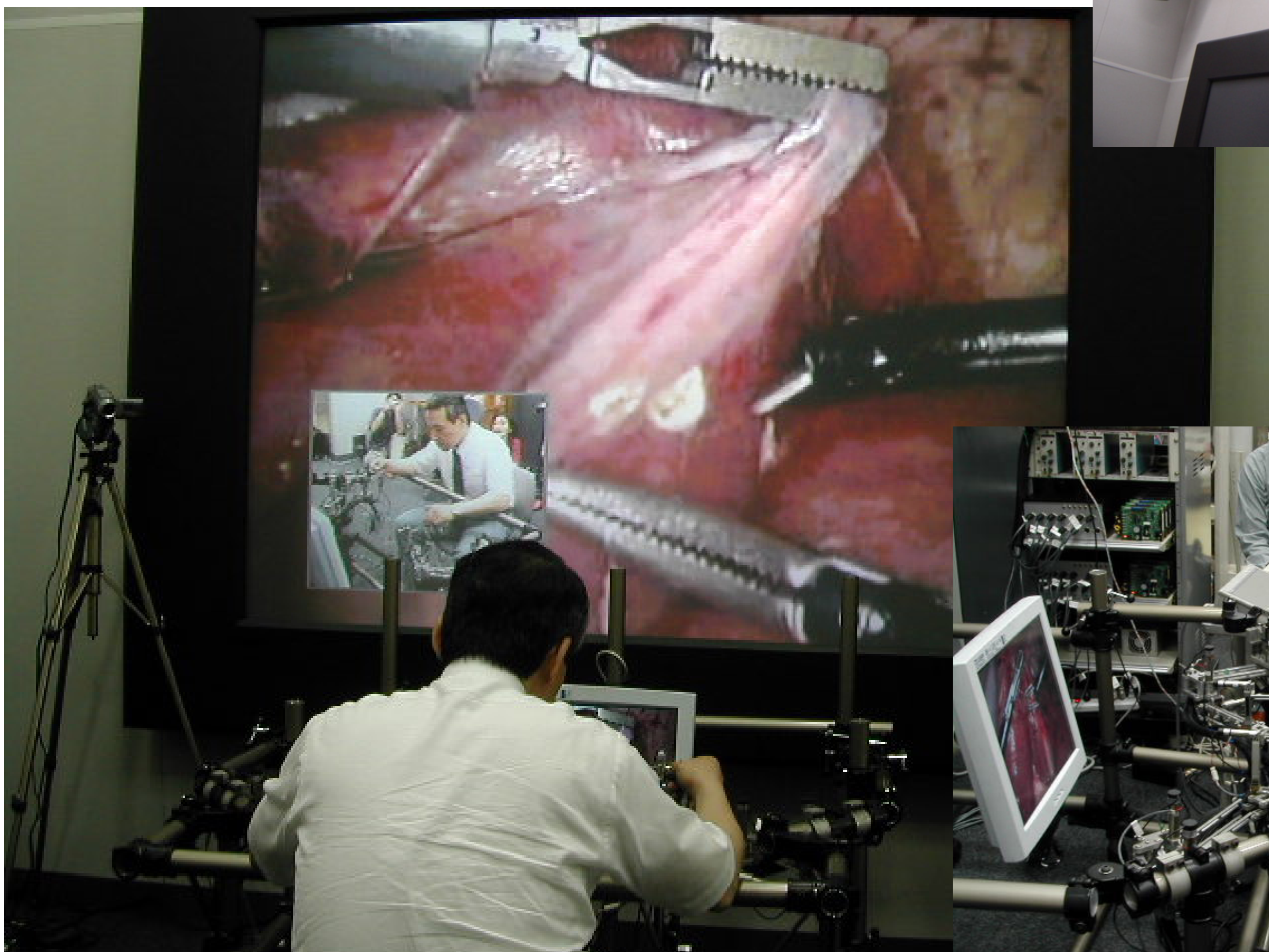
Master manipulator with force feedback and gravity compensation capability



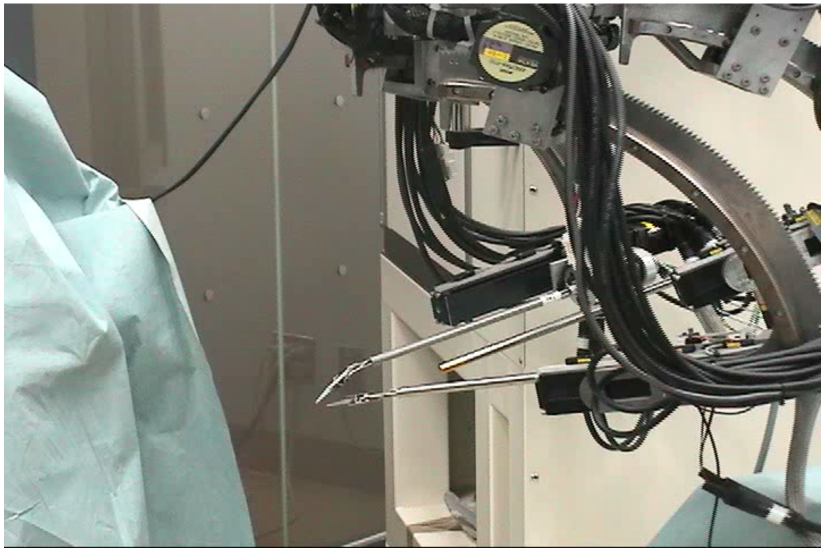


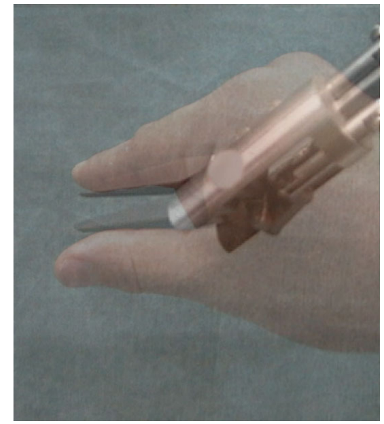
It is important to determine the standard between the master and slave manipulator.

Multi-media cockpit

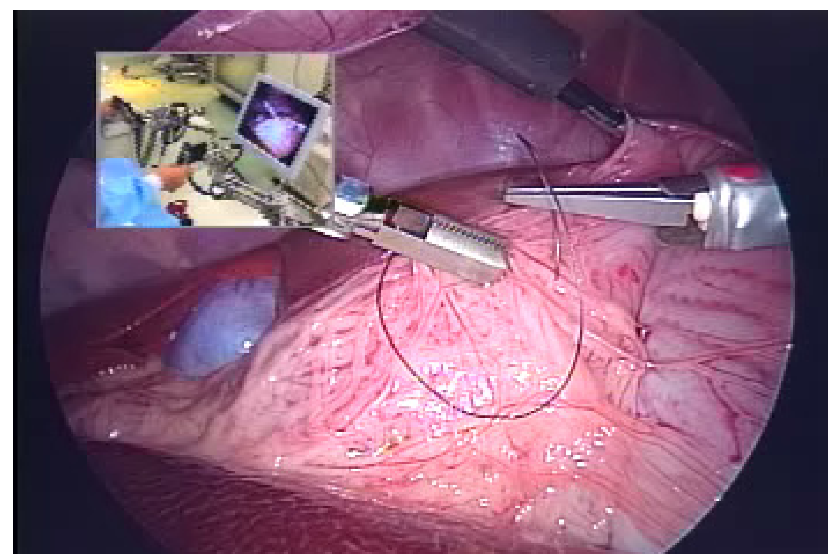


2 d.o.f. bending forceps with link mechanism

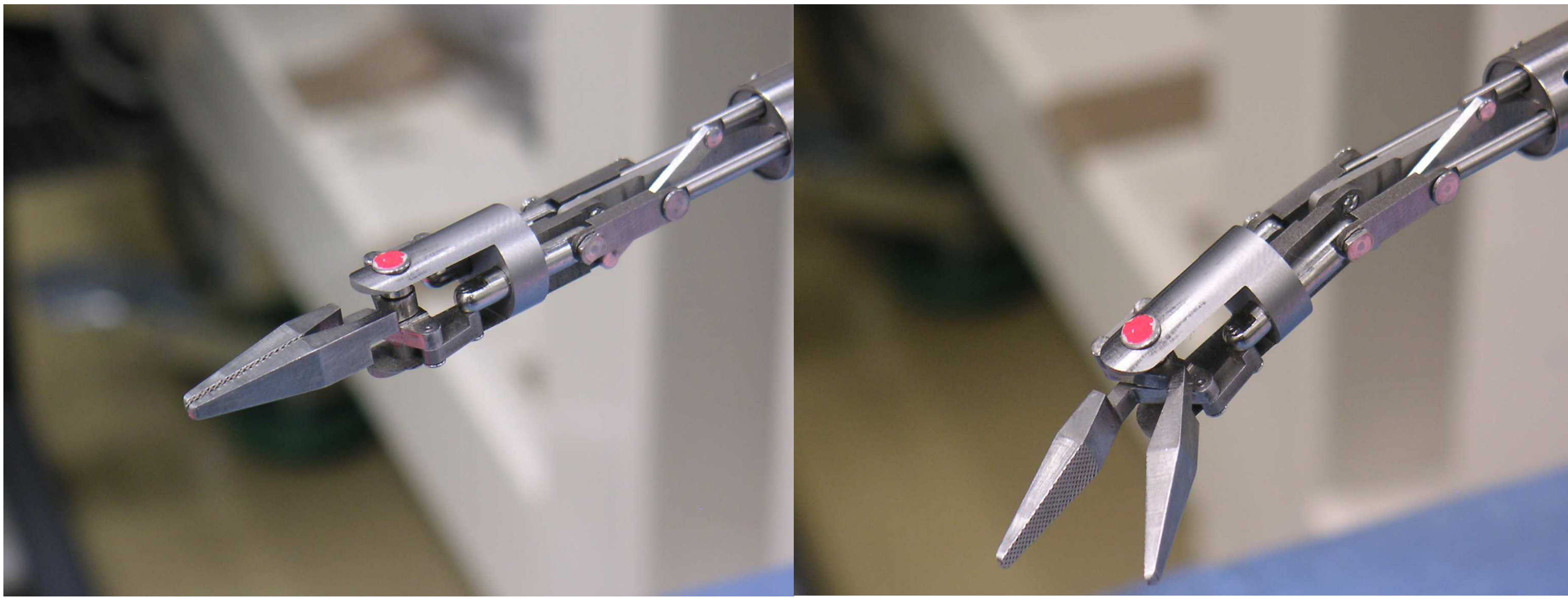


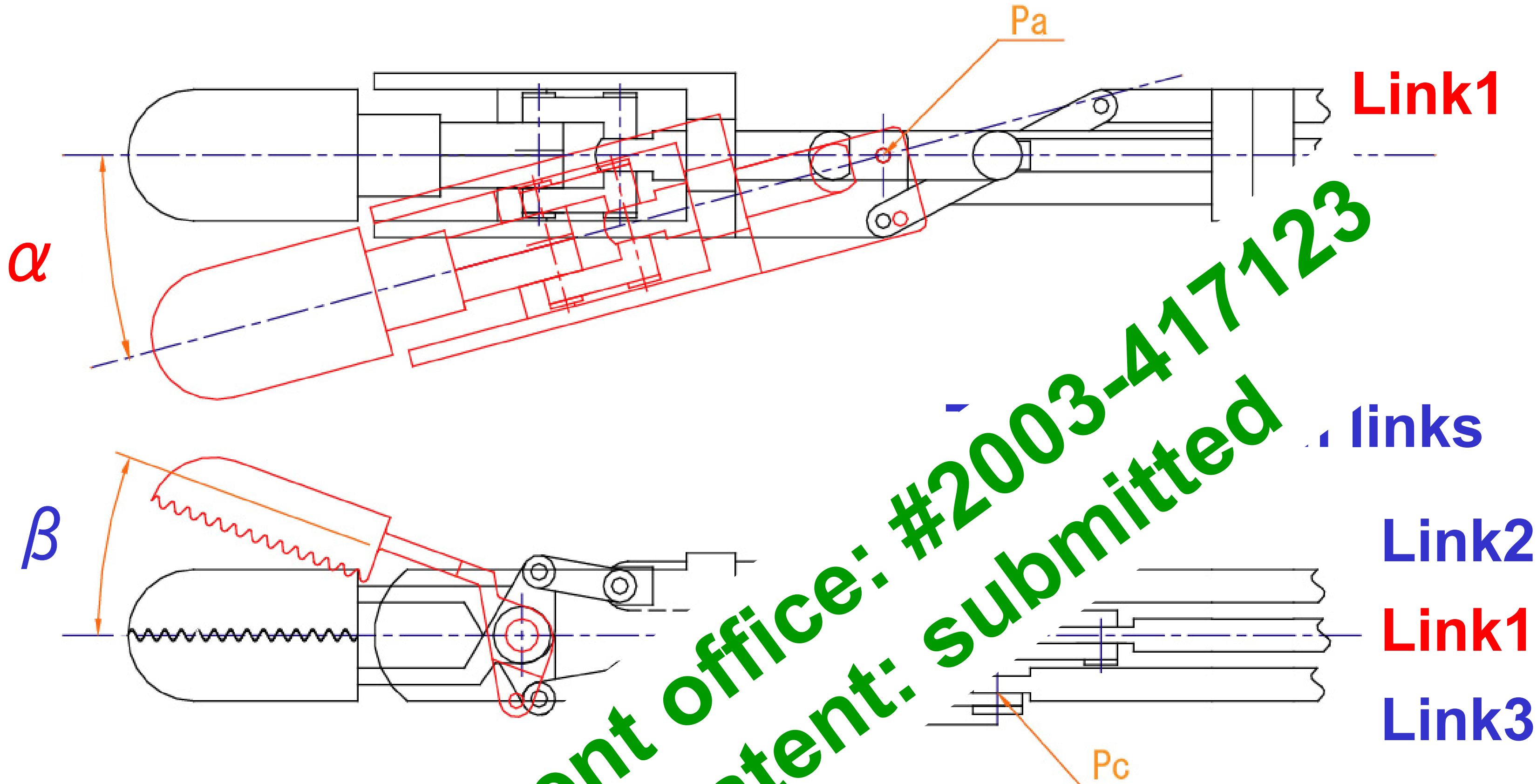


Coordinate system transformation between master and slave manipulators



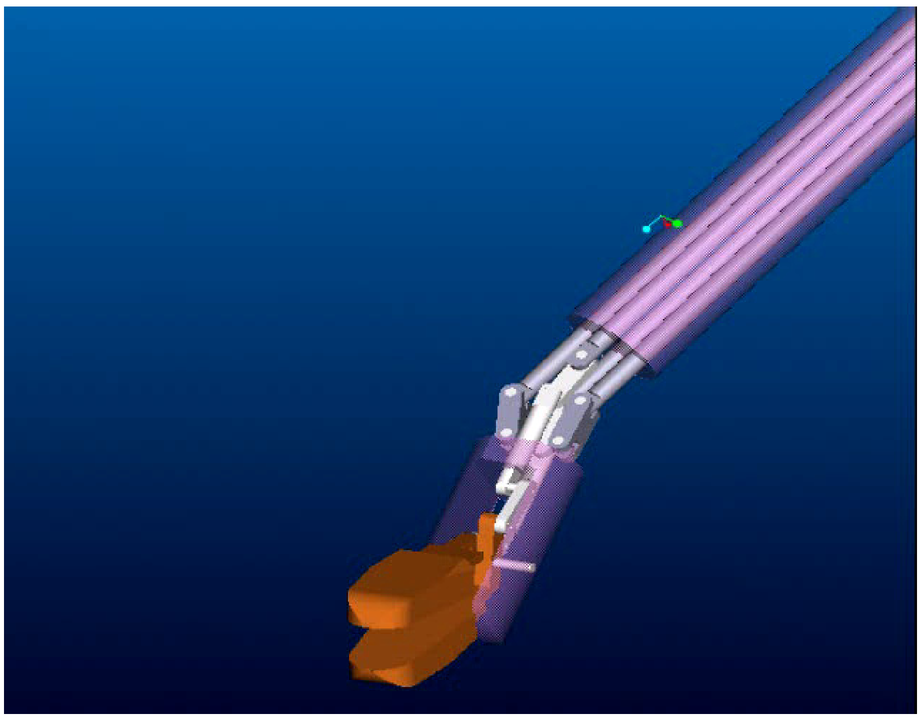
Link driven type 2 directional bending forceps

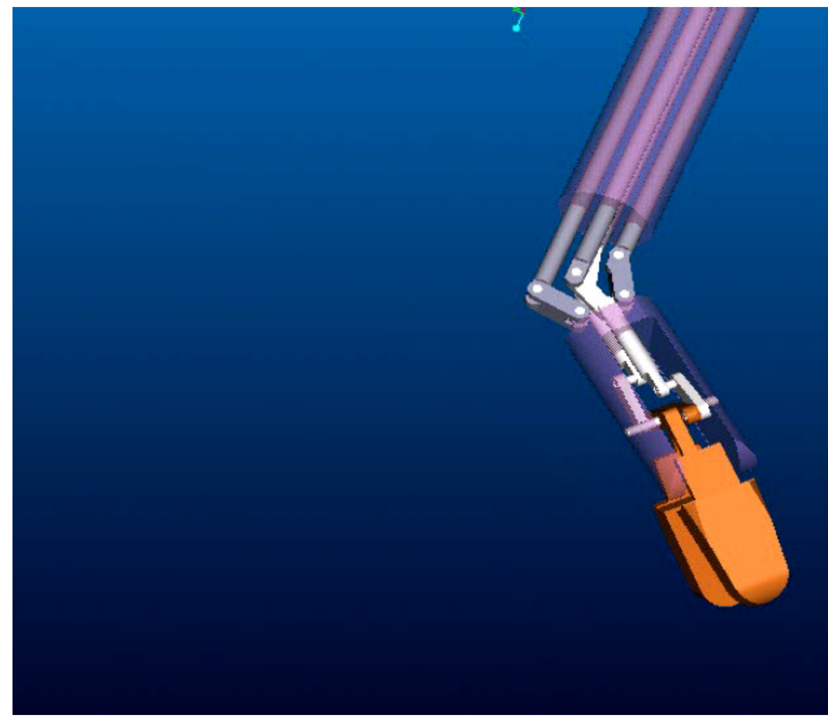




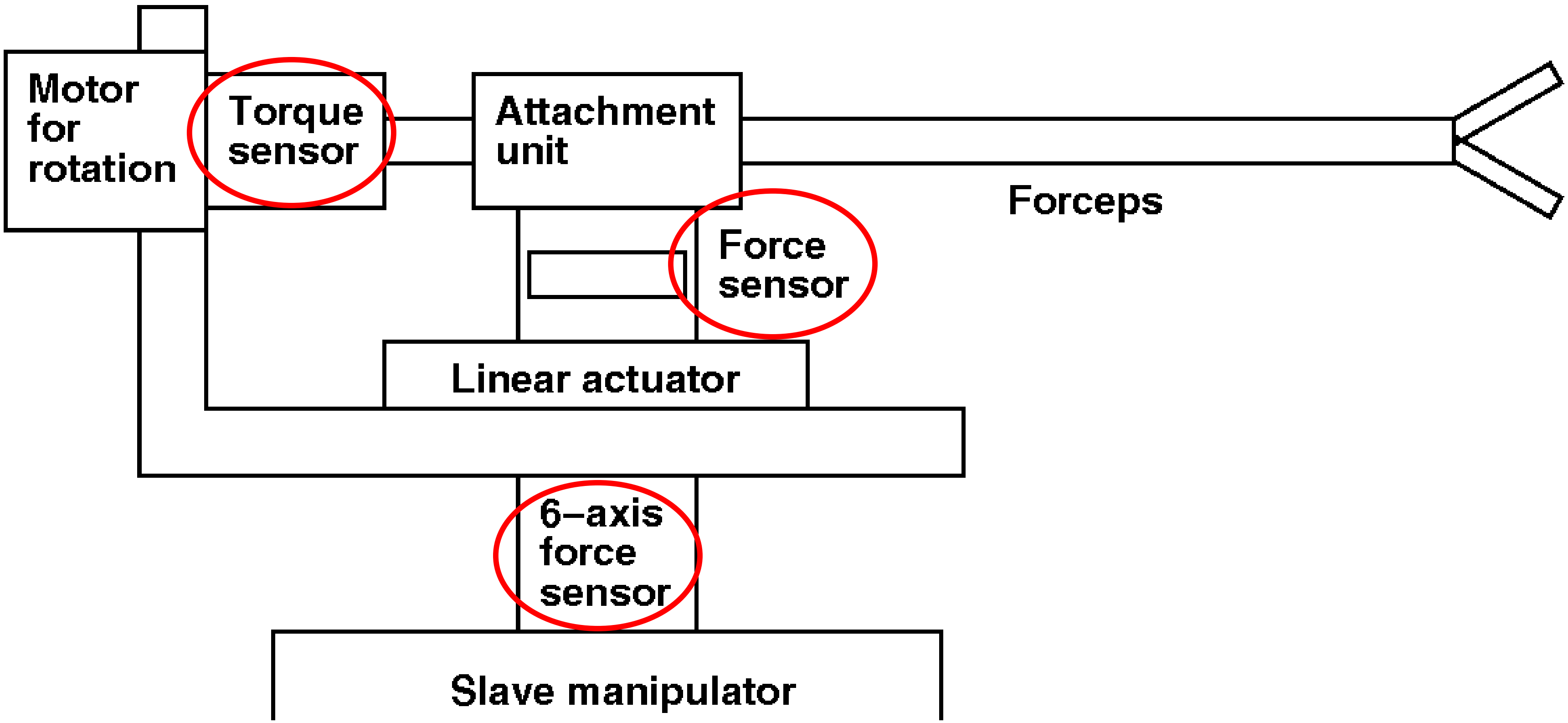
- The α-axis is driven by Link1.
- The crank mechanism generates bending motion.
- Transmission links are prepared to transmit the motions of Link2 and Link3 over the α-axis for β1- and β2-axis.
- β1- and β2-axis realize independent blade motion. generate bending and grasping motion.

Bending motion in 2 d.o.f. and a grasp motion

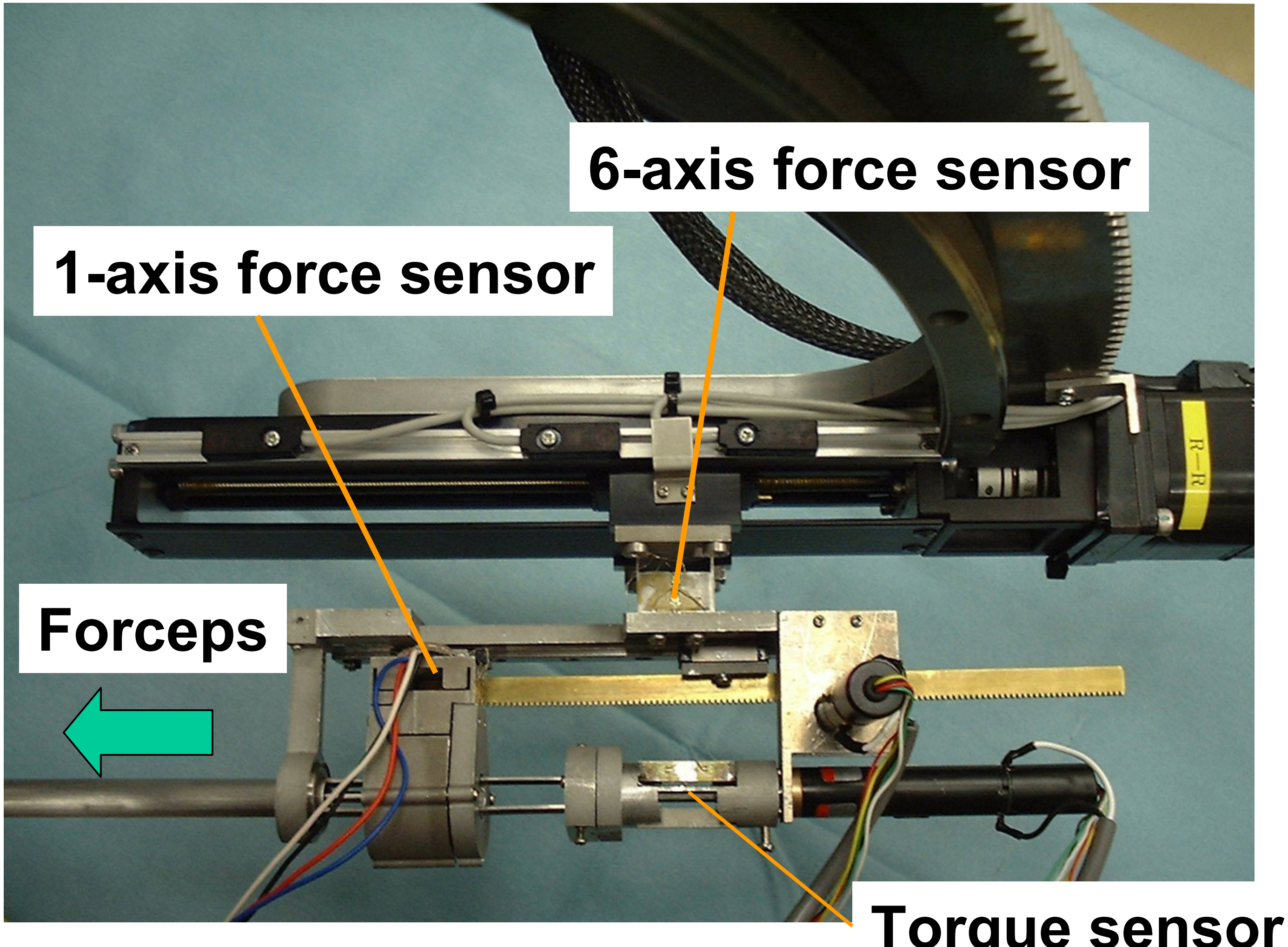




Structure of the active forceps with multi-axis force sensing capability

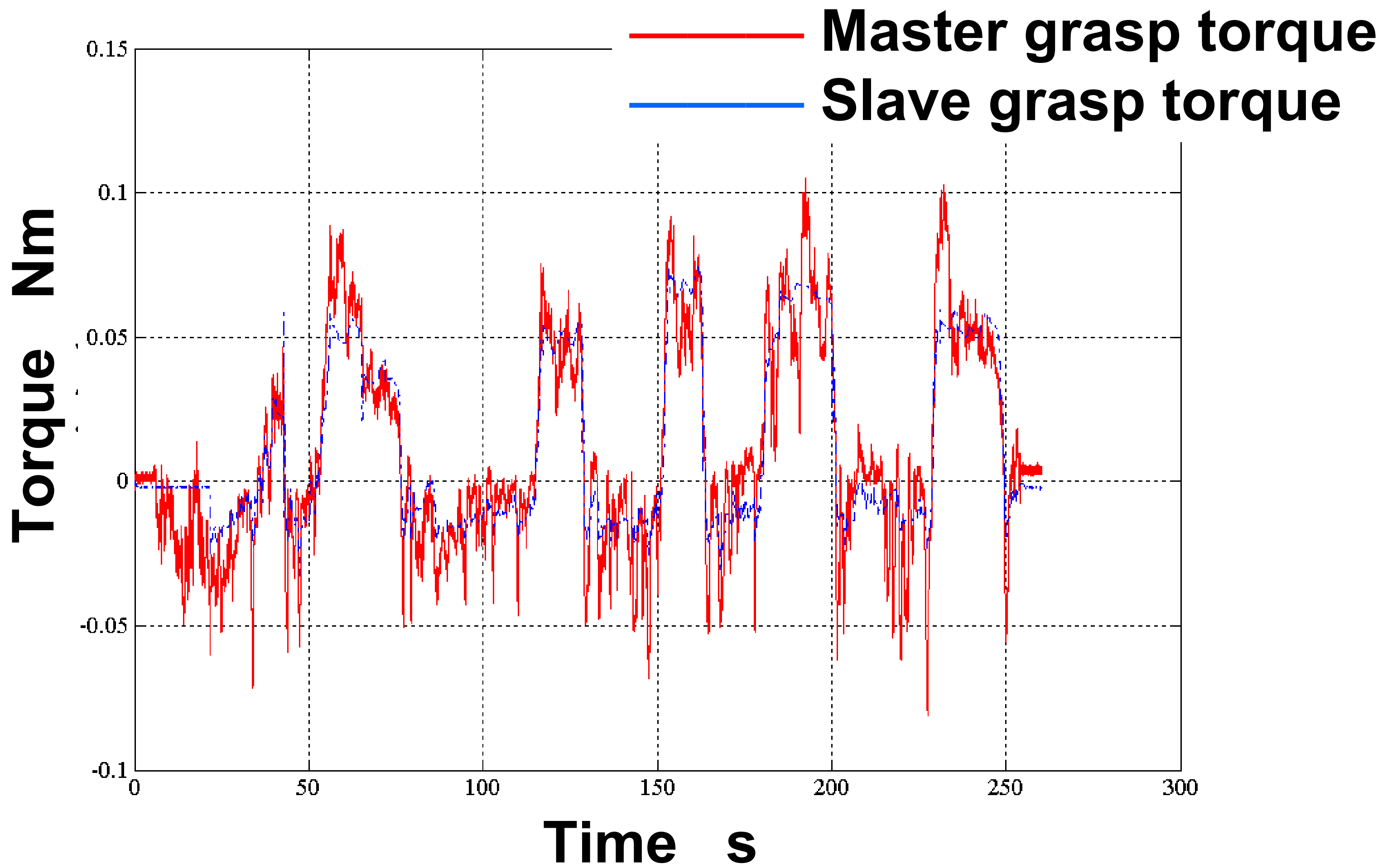


Force sensing part of the active forceps

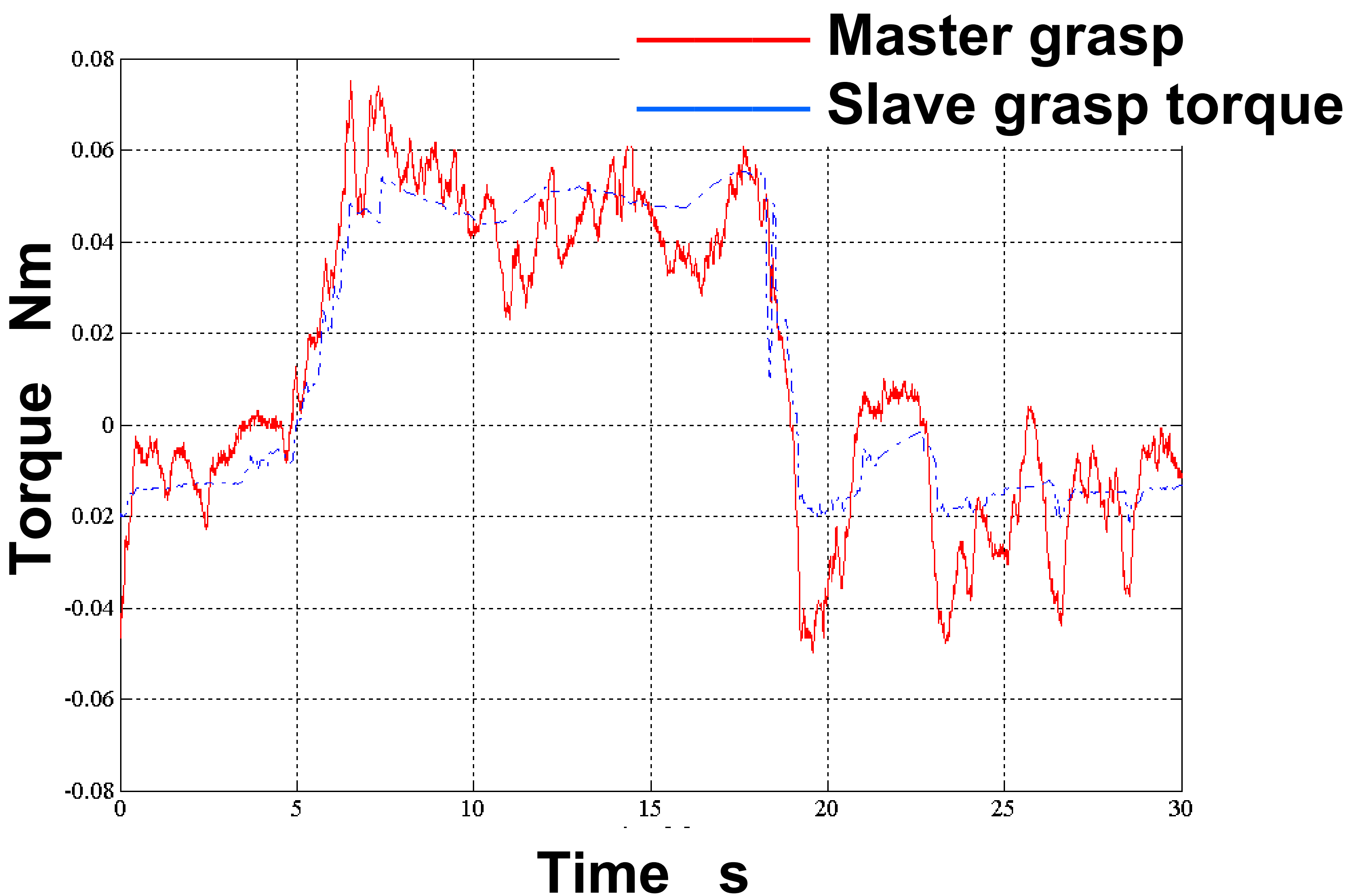


To avoid the sterilization and irrigation problem, force sensors are installed at the base part of the forceps.

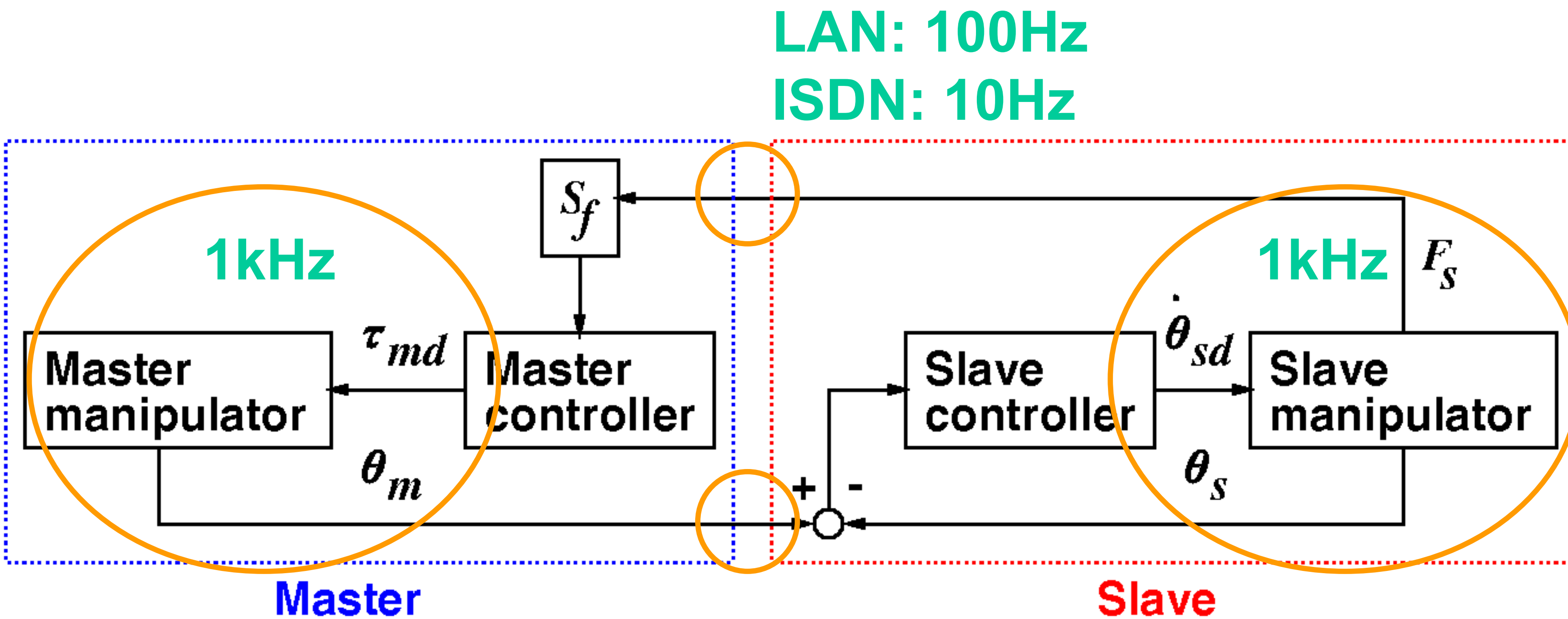
Response of grasp torque



Response of grasp torque



Control algorithm



S_f : Force feedback gain

F_s : Force applied to an object by the slave manipulator

θ_m : Position of master manipulator

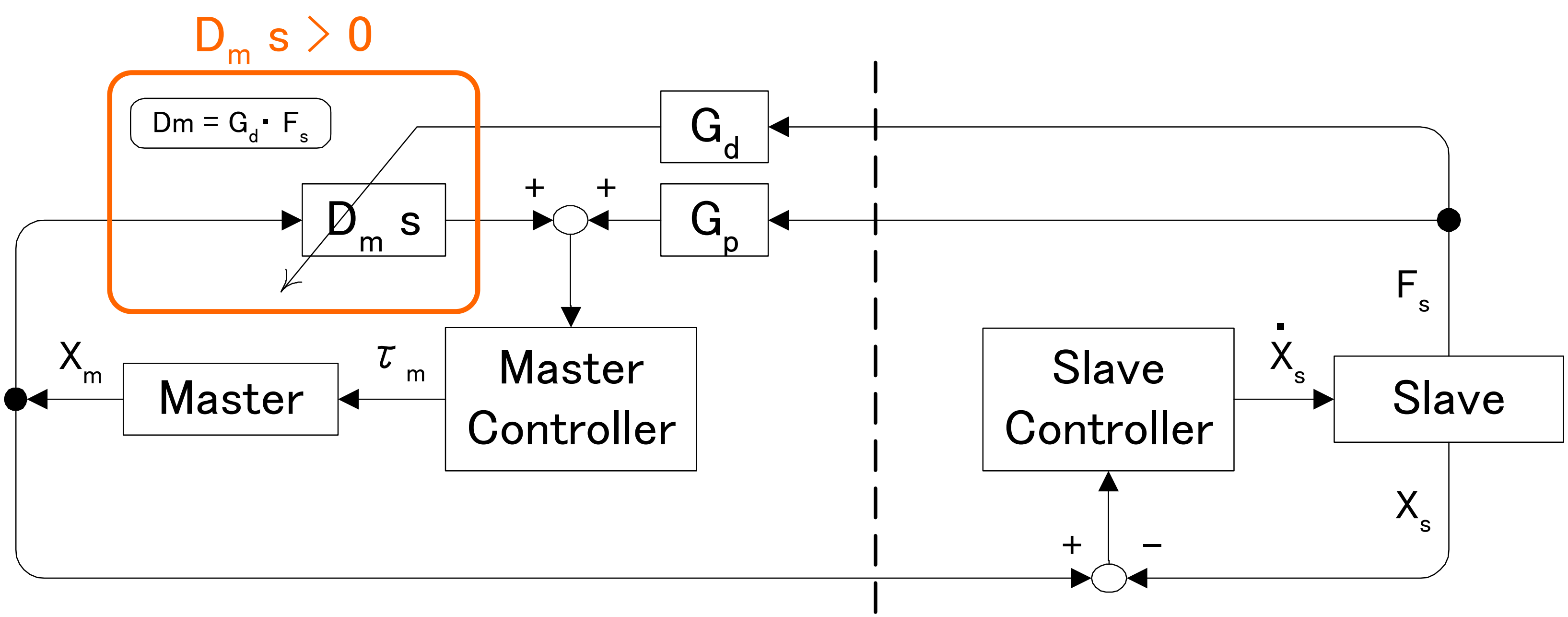
θ_s : Position of slave manipulator

θ_{sd} : Desired position of the slave manipulator

τ_{md} : Desired torque of the master manipulator

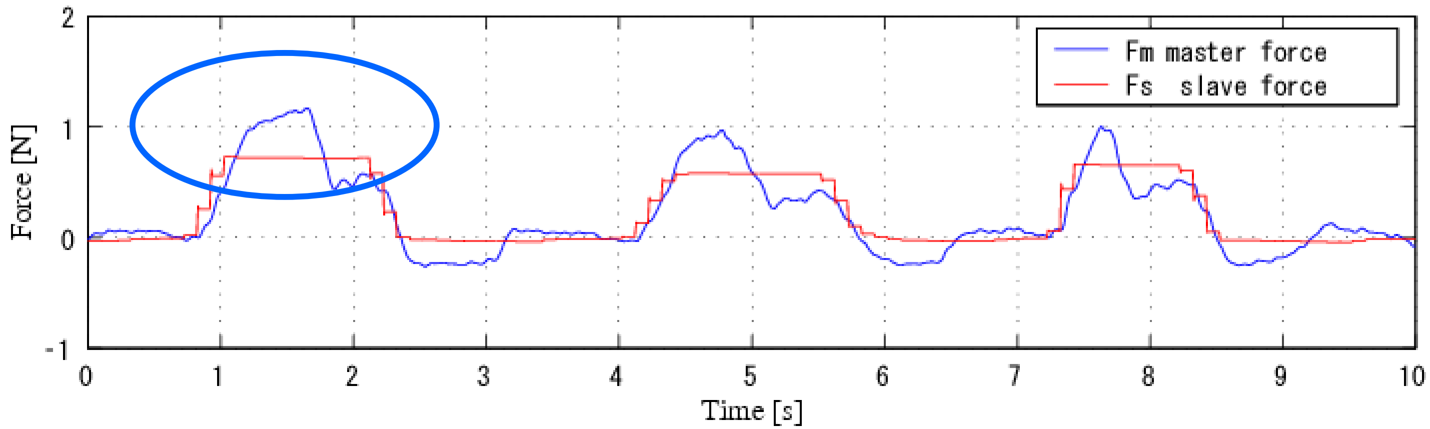
Augmented presentation of contact force

- **A damper element Dm was added to the force reflection controller.**
- **It generates viscosity impedance to the master manipulator when contact force occurs between the slave manipulator and an object.**

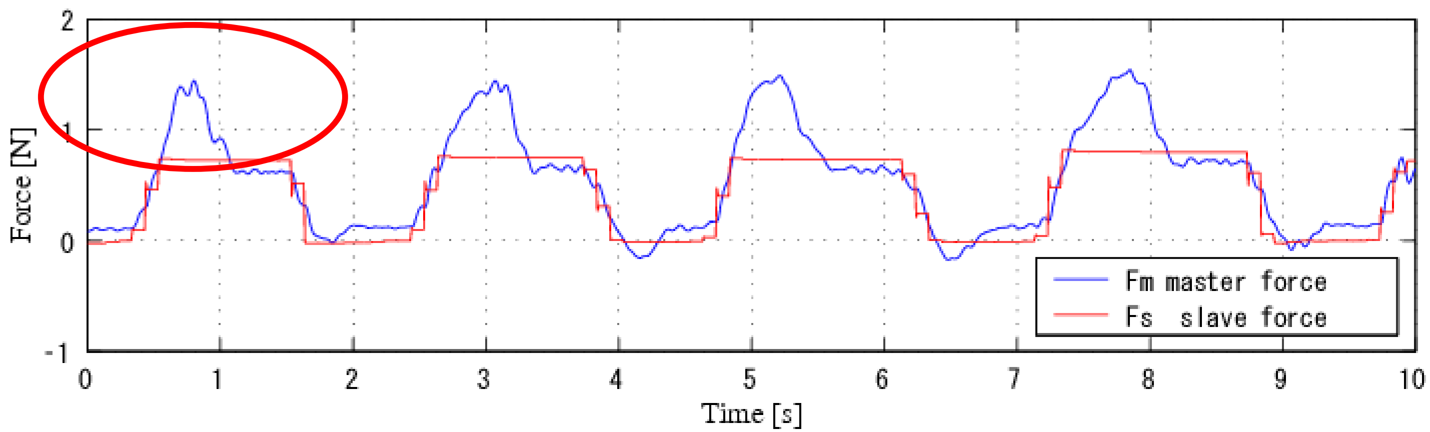


X_m : Master position	F_m : Master force	G_p : Gain of P control
X_s : Slave position	F_s : Slave force	D_m : Damper Element

The active contact force, caused by the master manipulator's motion, is augmented because the damper element is used.



Conventional bilateral control method



Augmented contact force presentation method

Previously determined force was successfully presented as a maximum value.

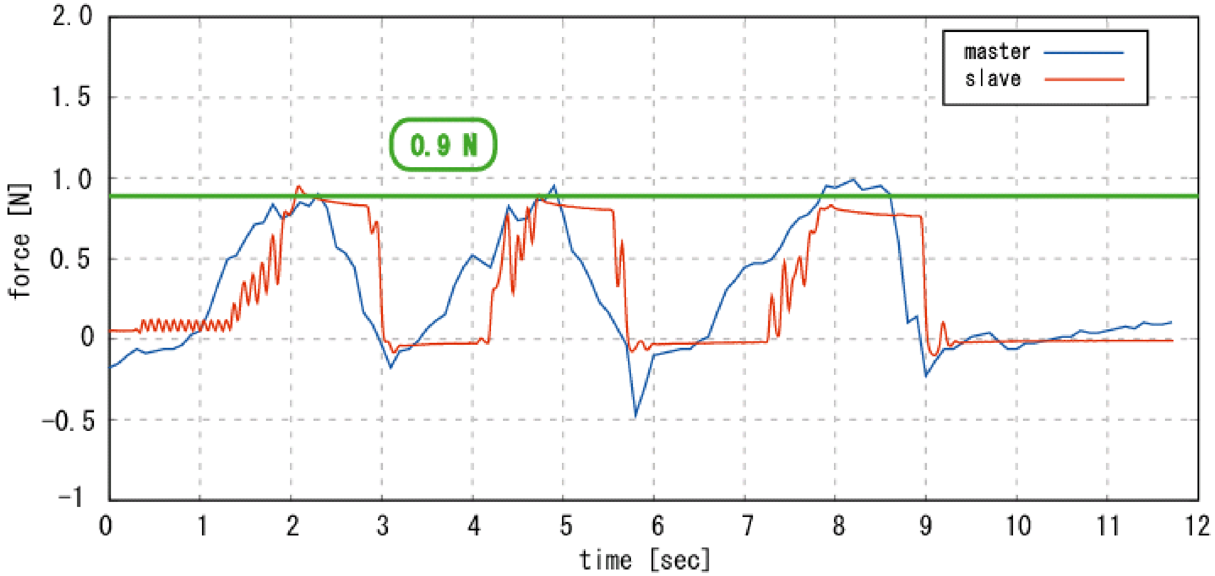
➡ Contact information was reliably presented to the operator.

The necessary time to reach the presented force maximum was small.

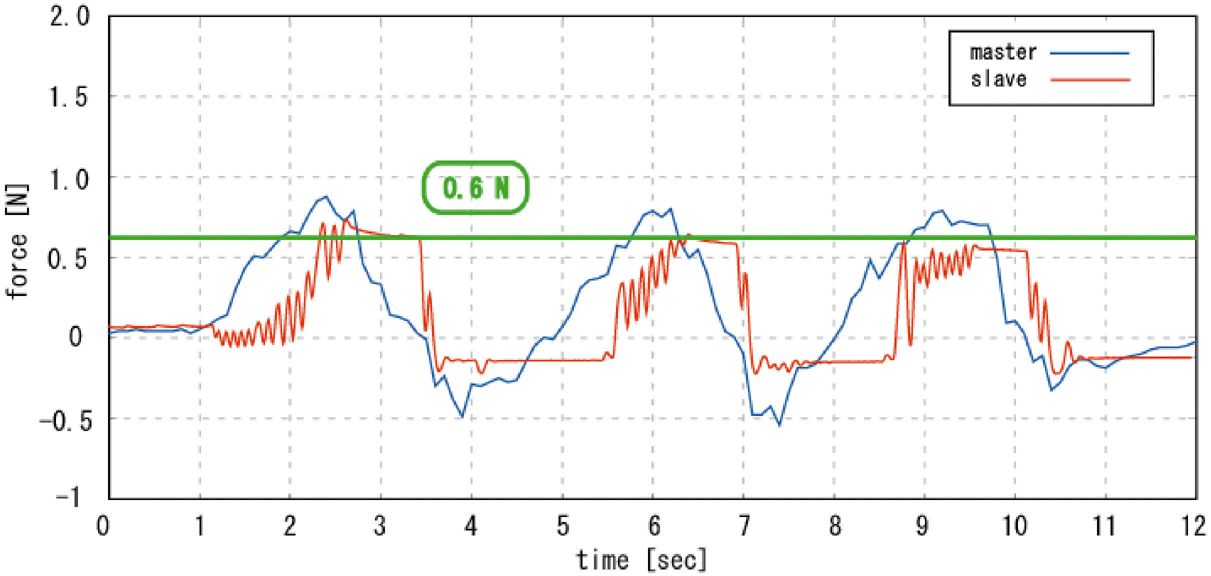
➡ Necessary time to perceive the contact is small.

The operability of the system was excellent.

Comparison of the maximum grasp force

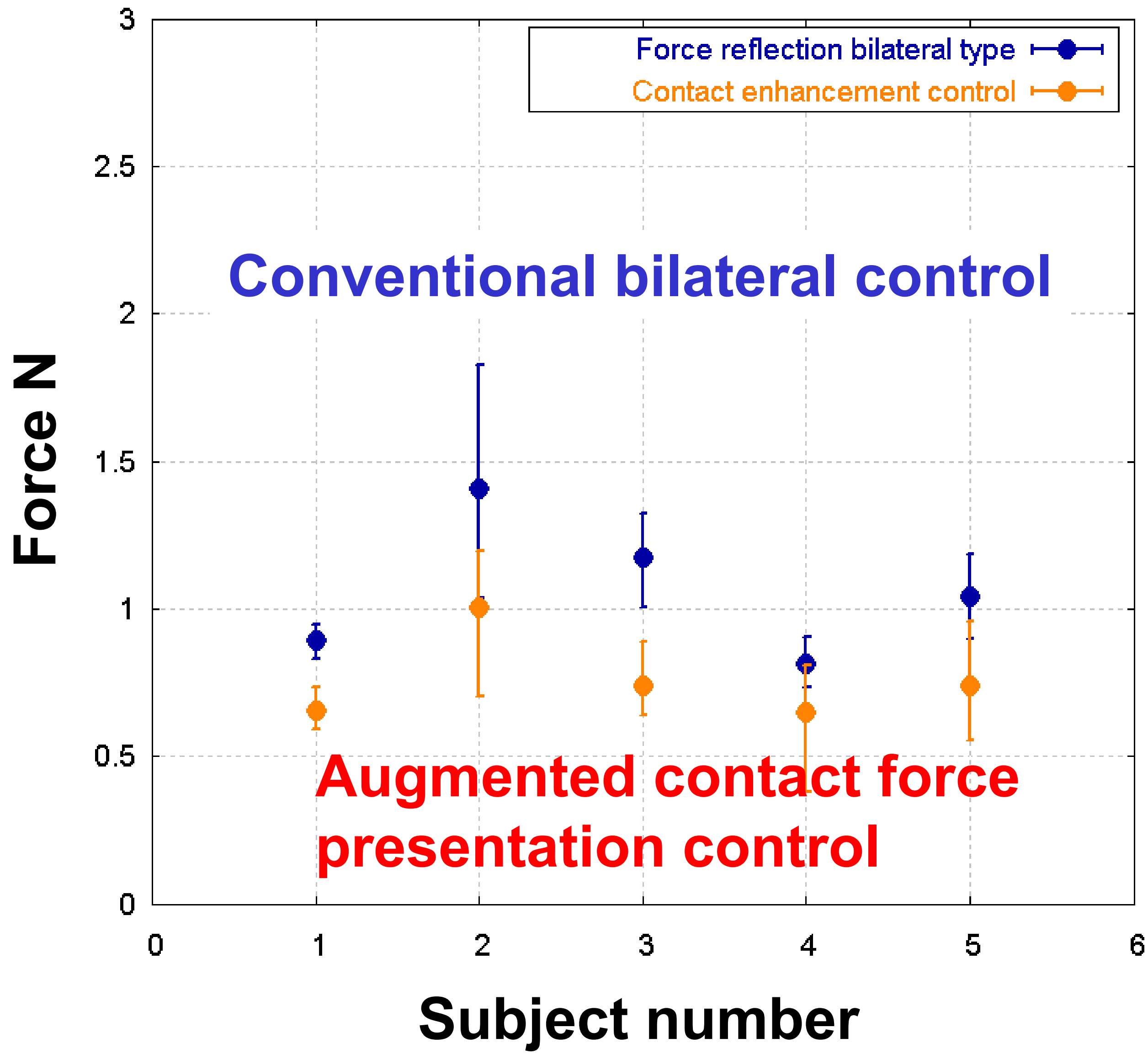


Conventional bilateral control



Augmented contact force presentation control

Comparison of the maximum grasp force



Maximum grasping force at the slave-manipulator

Subject	1	2	3	4	5
Conventional bilateral [N]	0.89	1.41	1.17	0.81	1.04
Augmented contact force [N]	0.66	1.00	0.74	0.65	0.74

Reduction ratio to feel the grasping force

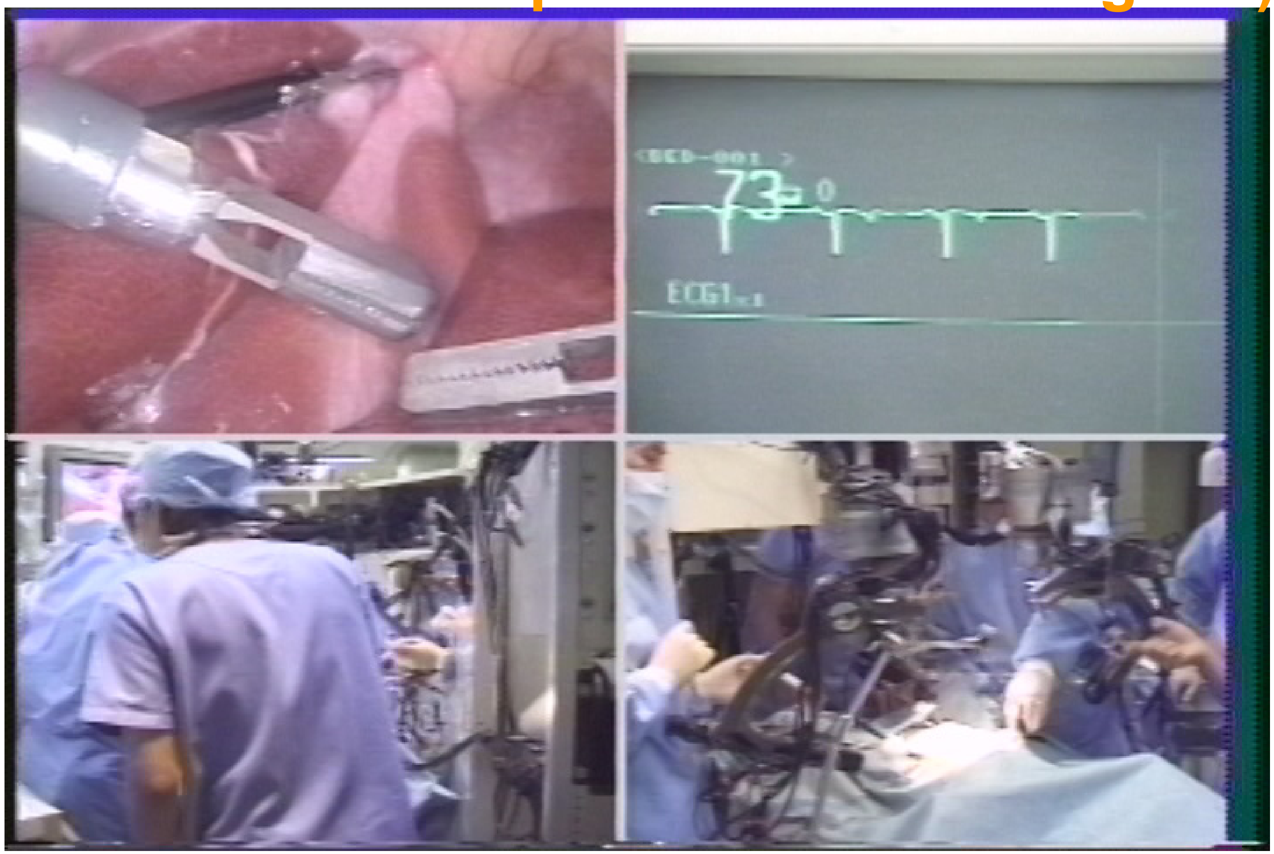
Subject	1	2	3	4	5
Reduction ratio [%]	26.4	28.7	37.0	19.7	28.8

The load reduction ratio was 28[%], on average.

Total operational environment transmission

Visual information from the endoscope

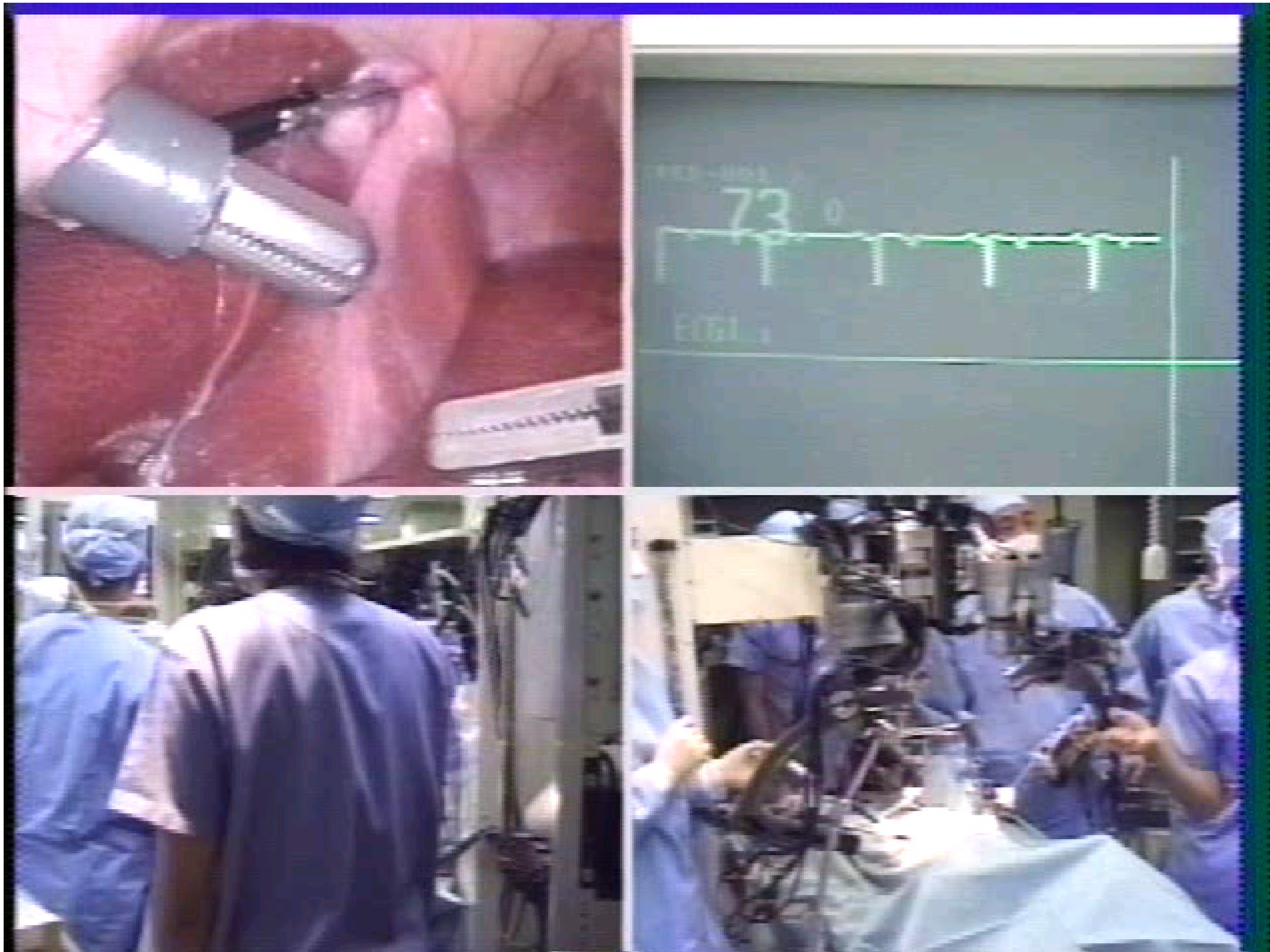
Vital signs (ECG: electrocardiogram)



The information of the assistant at the surgical site

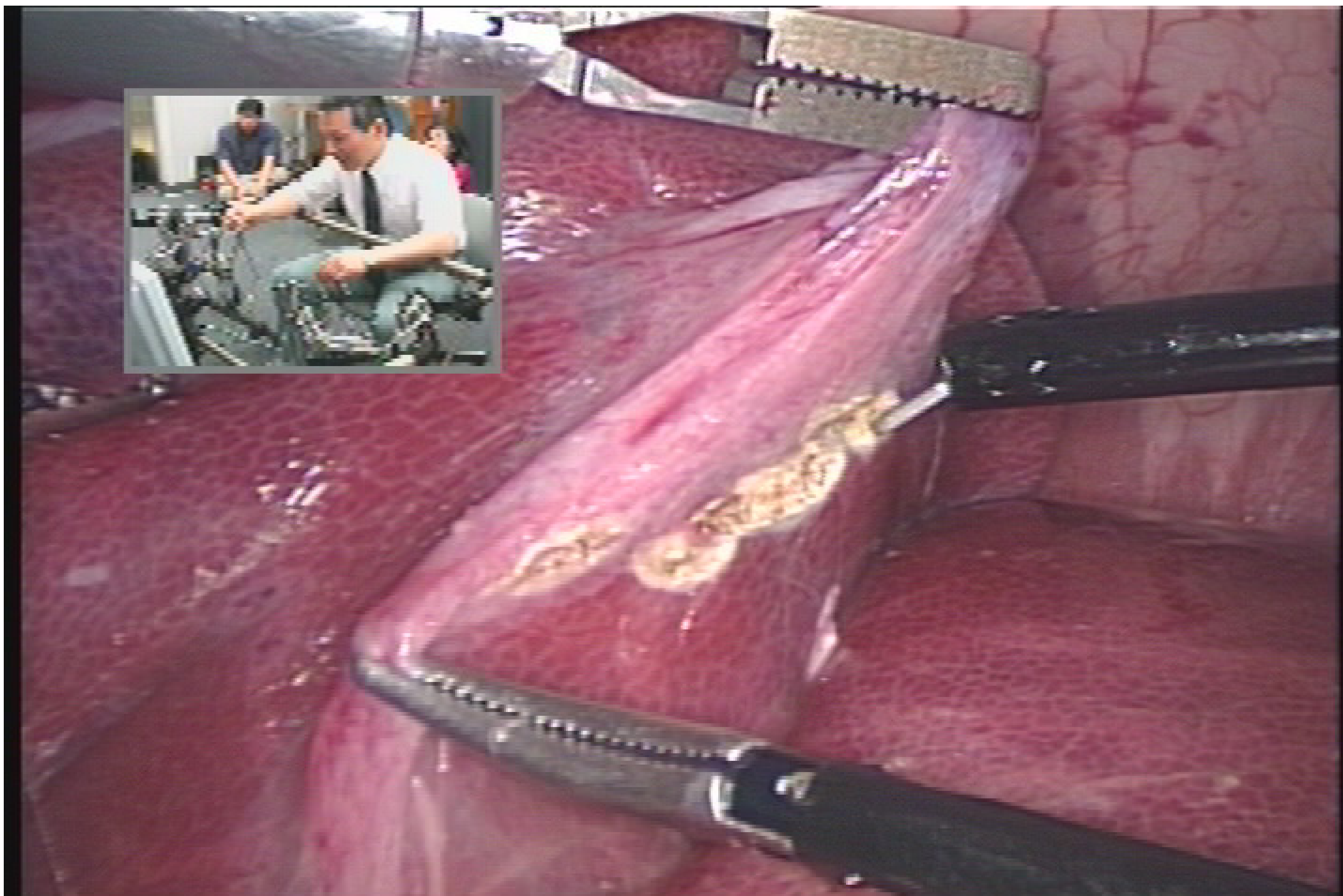
Status of the slave manipulator

Remote surgical experiment

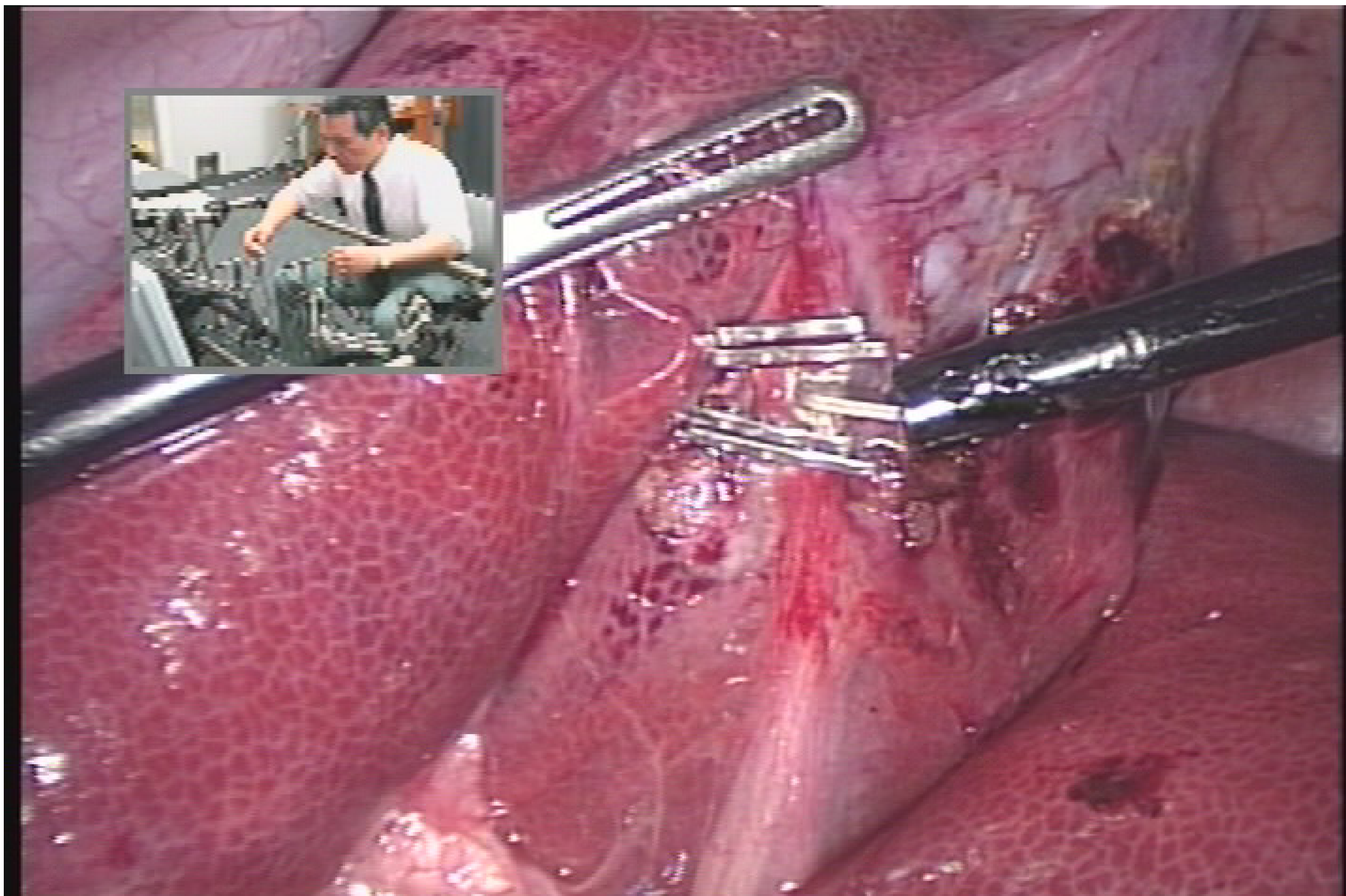


using INS128x3

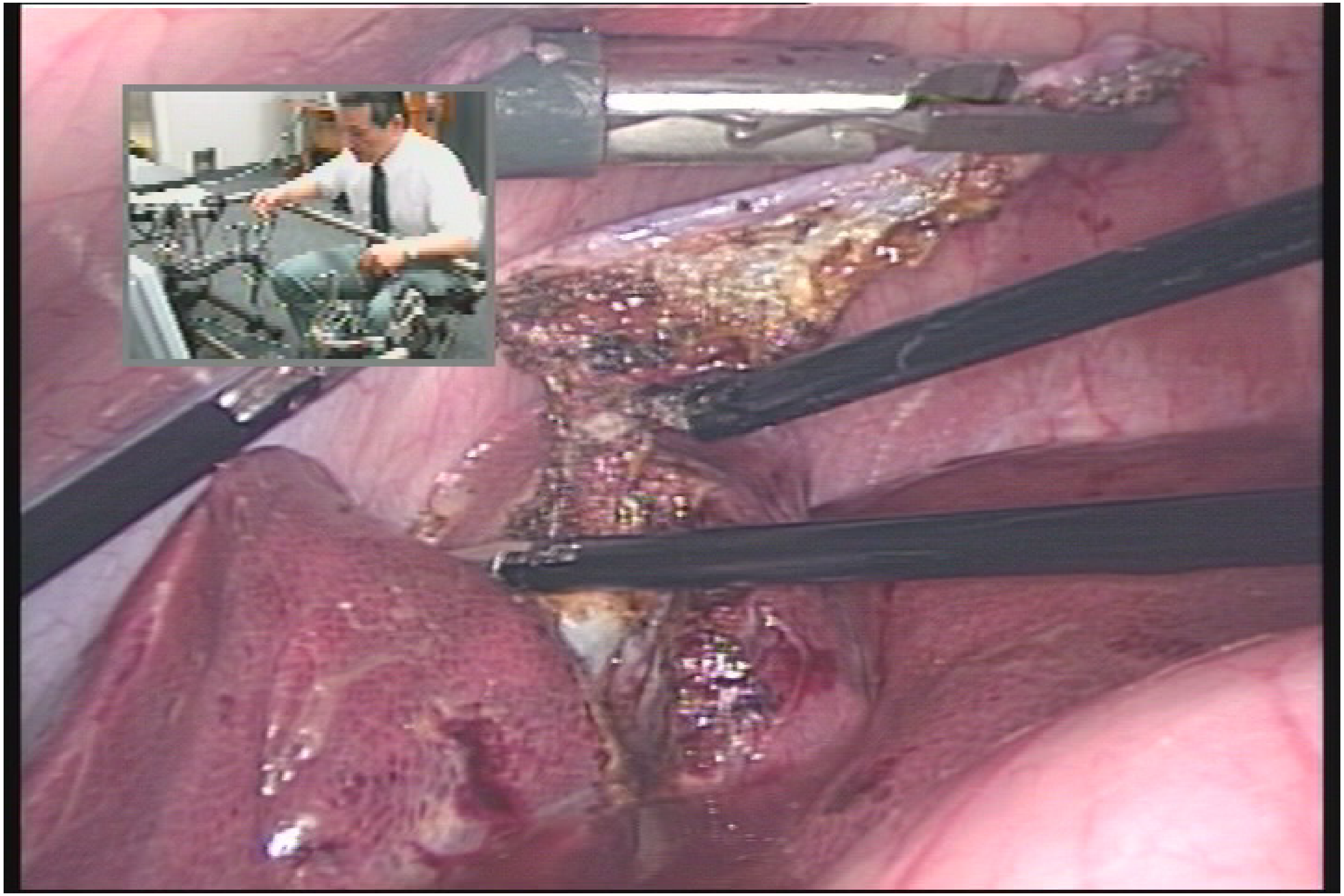
Cut part is marked using a radio knife.



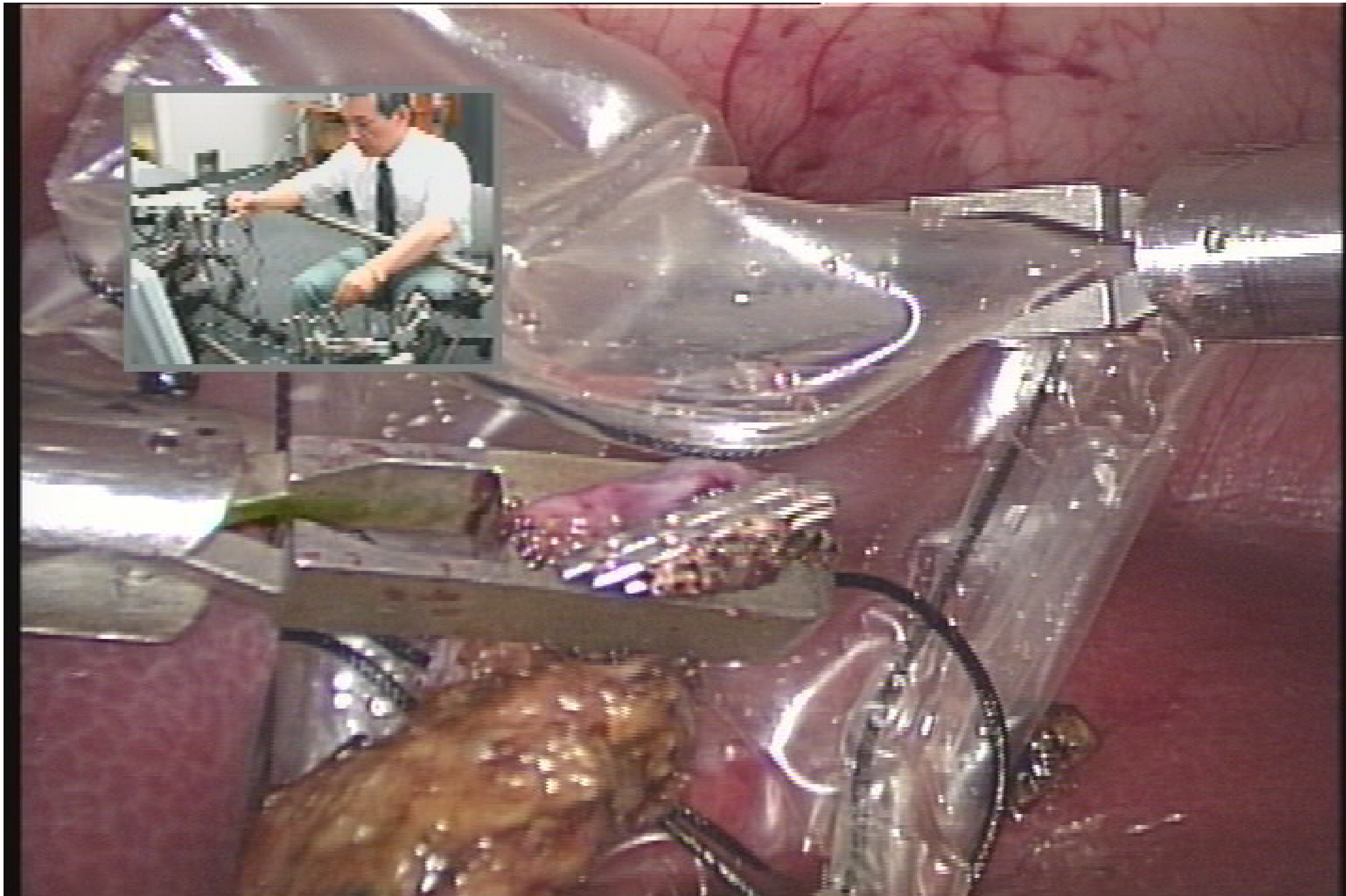
The cystic duct is stapled and then it is cut off using the radio knife.



The gallbladder is almost cut.



The cut off gallbladder is collected.



Remote cholecystectomy experiment

August 8, 2003

in-vivo remote surgery experiment

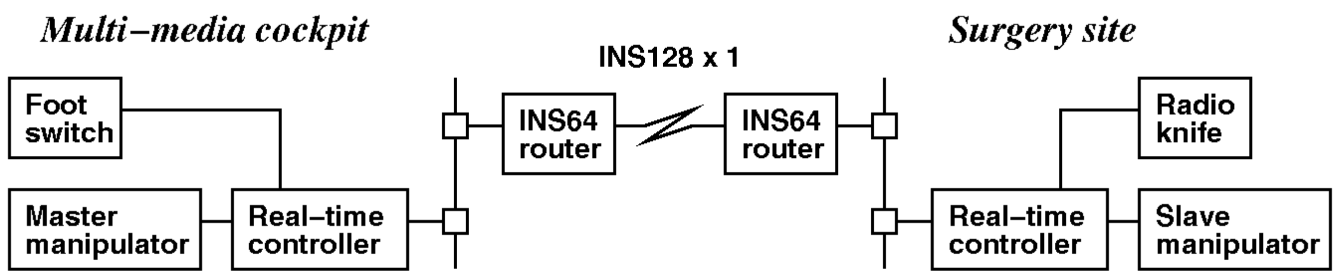
Operation Sight:
The Univ. of Tokyo (Tokyo)
Surgery Sight:
Tyco Health Care ATC (Shizuoka)

NML Mitsuishi-Warisawa Lab.
Dept. of Engineering Synthesis,
School of Engineering,
The University of Tokyo ,

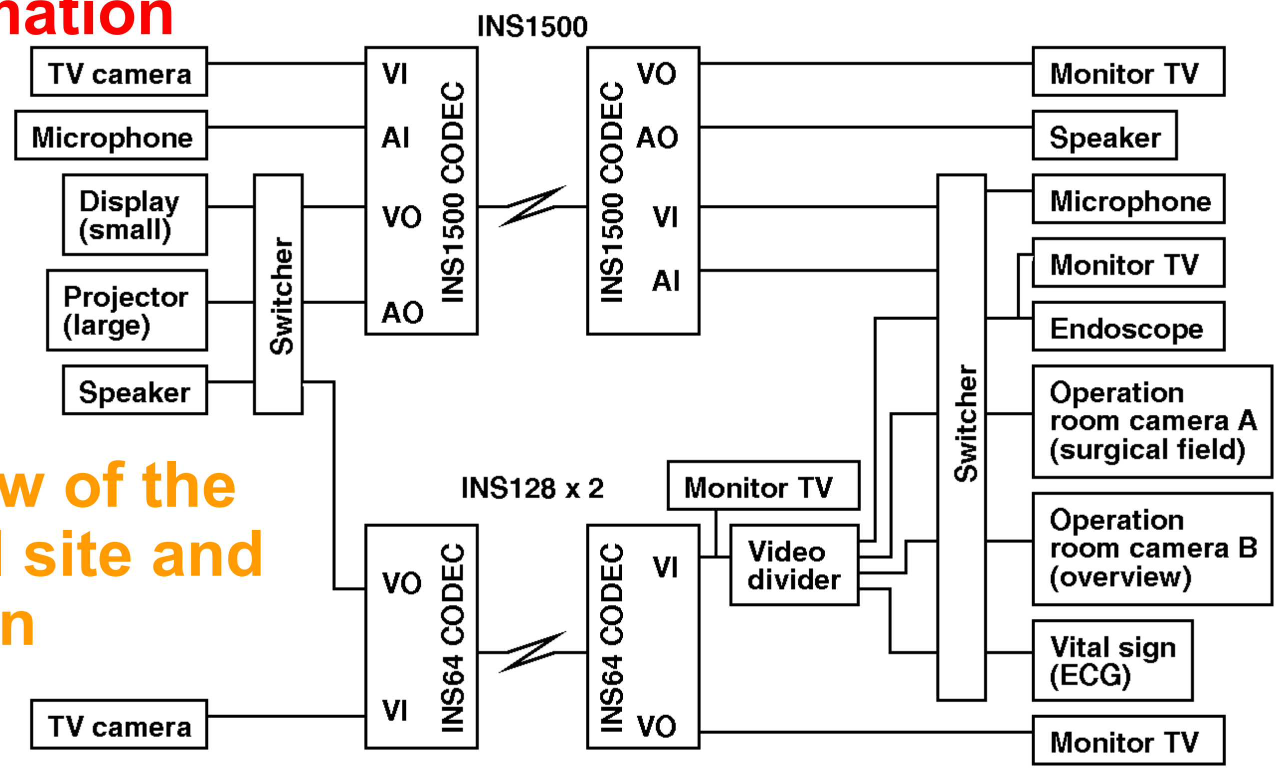
using INS1500 + INS128x3

Experimental set up using INS1500

Robot control information



Visual information from the endoscope and auditory information

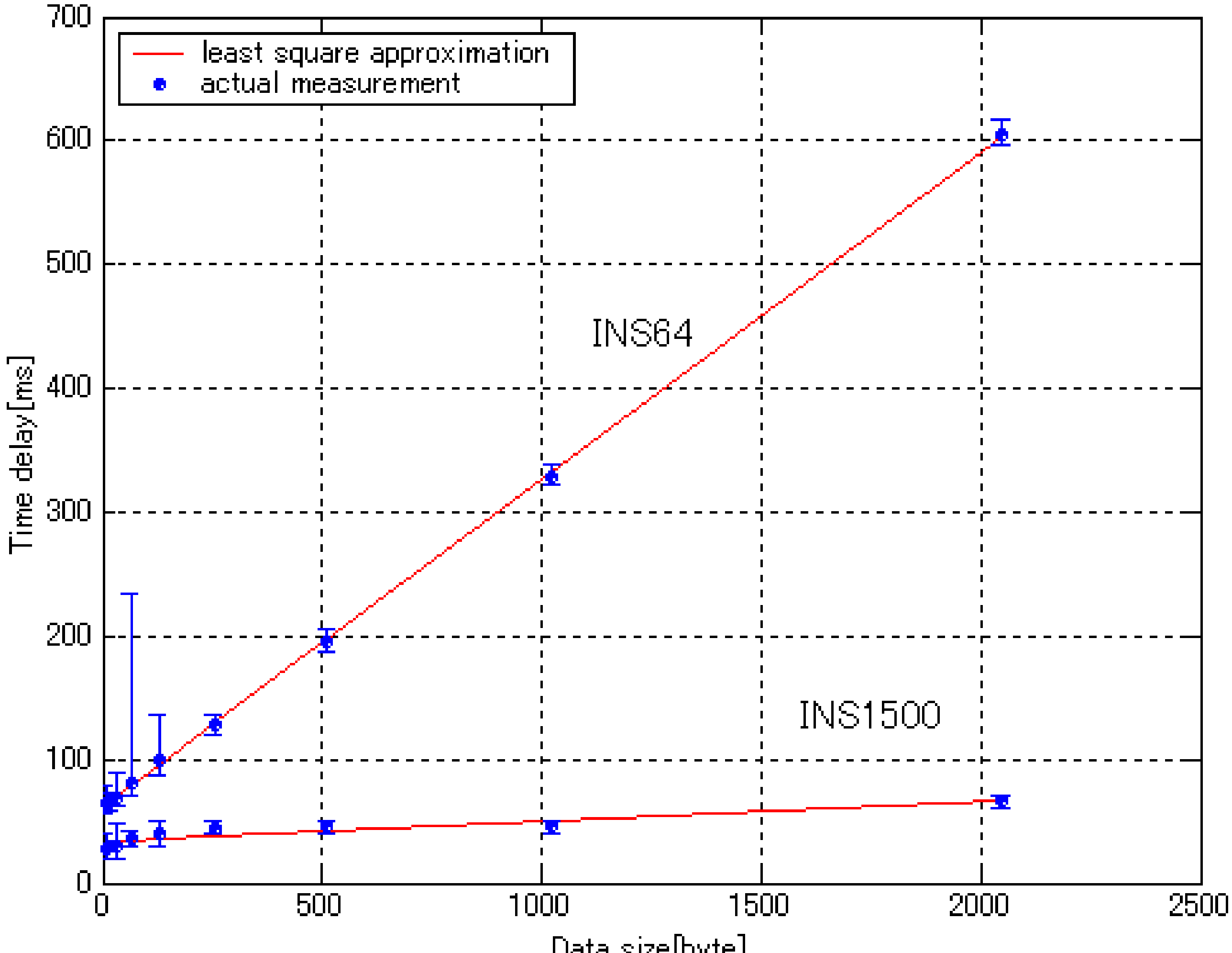


Overview of the surgical site and vital sign

Experimental results using INS1500

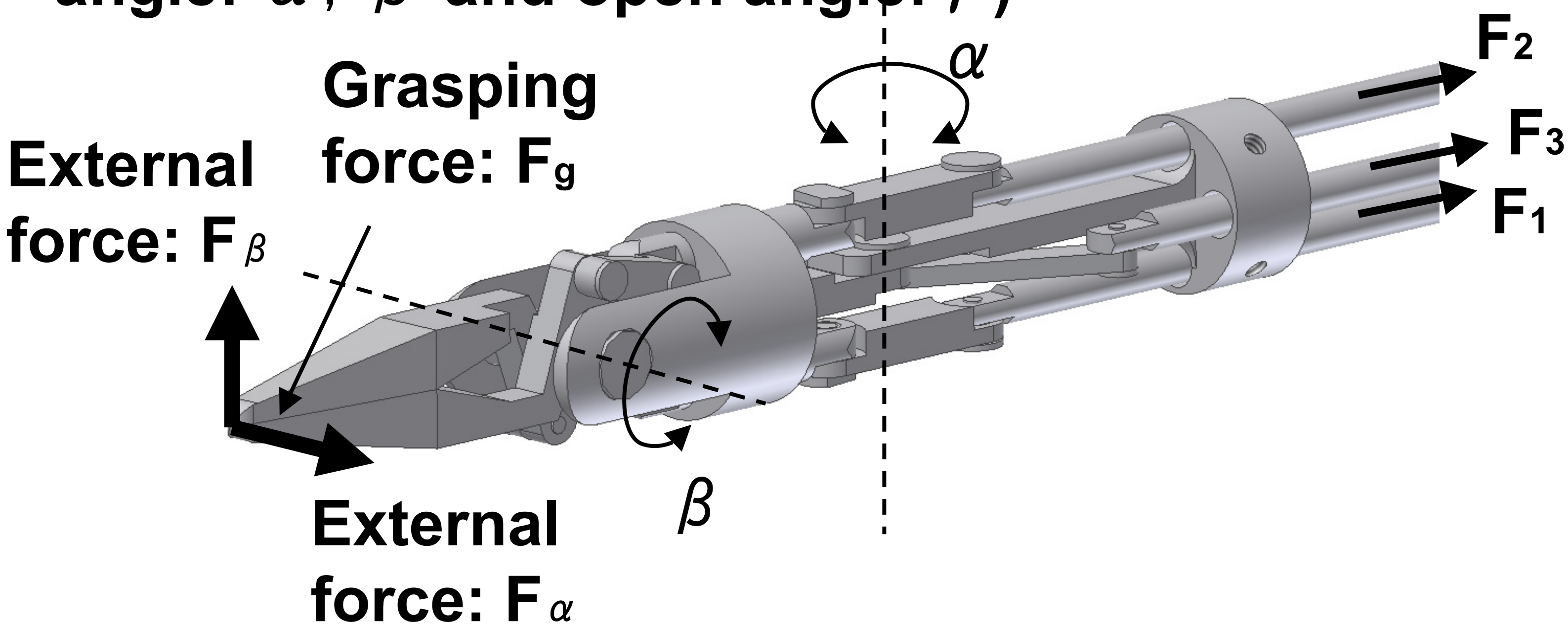
- Precise blood vessel can be noticed because the quality of the visual information from the endoscope was improved.
- Time delay between master and slave manipulators was 50 ms and 390 ms for robot control information and visual information transmission, respectively. However, the stress of the operator was not reported.
- Remote surgical experiments were successfully accomplished 5 times.
  Clinical test was executed after 6 times animal experiments in the case of Zeus.

Comparison of INS64 and INS1500: Relation between data size and the time delay using “ping” command



Measurement method

Calculate the grasping and external force from the axial force (F_1, F_2, F_3) and the current posture (bending angle: α, β and open angle: γ)

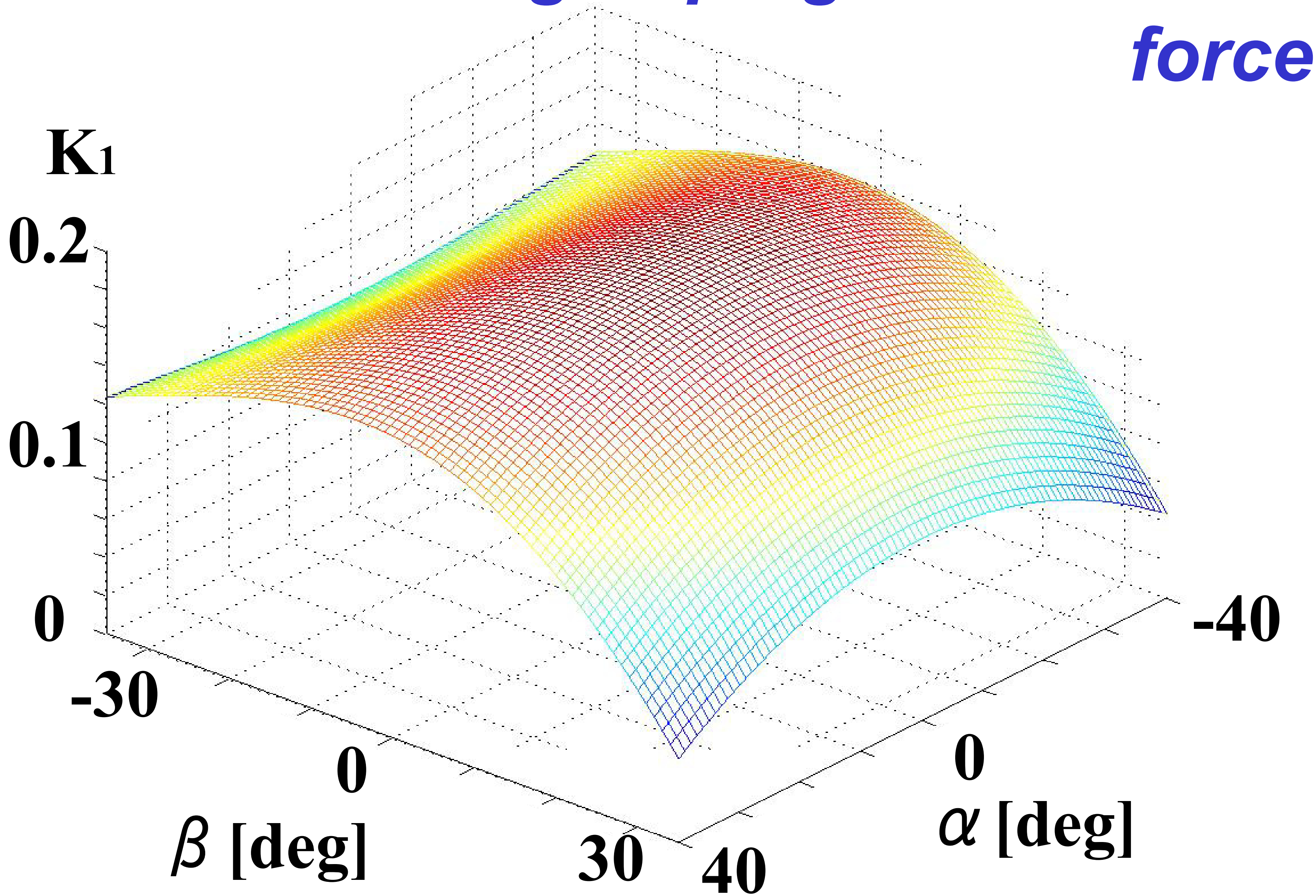


$$F_g = K_1(\alpha,\beta,\gamma)\cdot F_1 = K_2(\alpha,\beta,\gamma)\cdot F_2$$

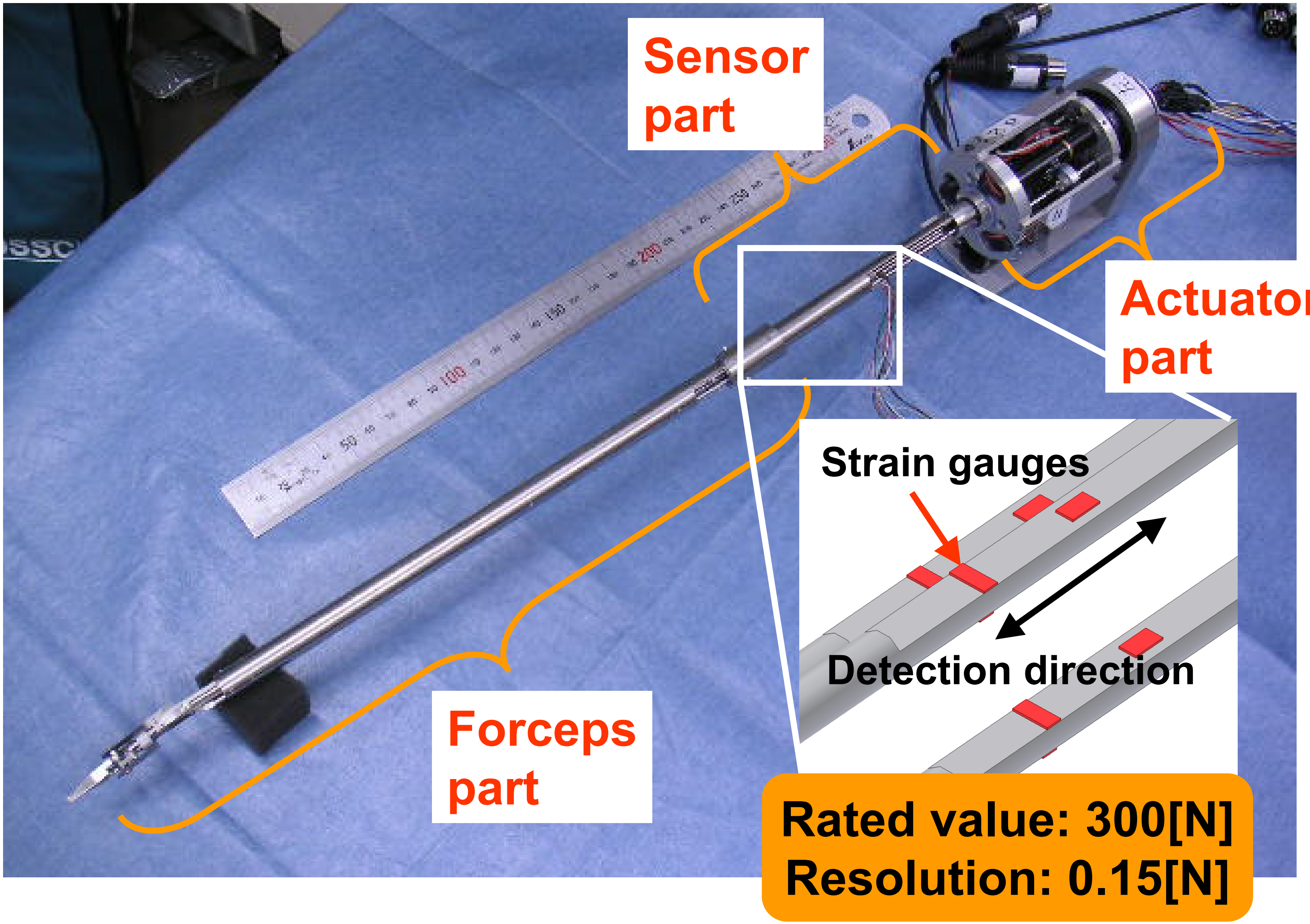
$$F_\alpha = K_3(\alpha,\beta,\gamma)\cdot F_3$$

$$F_\beta = K_2(\alpha,\beta,\gamma)\cdot F_2 - K_1(\alpha,\beta,\gamma)\cdot F_1$$

Calculation of grasping and external force

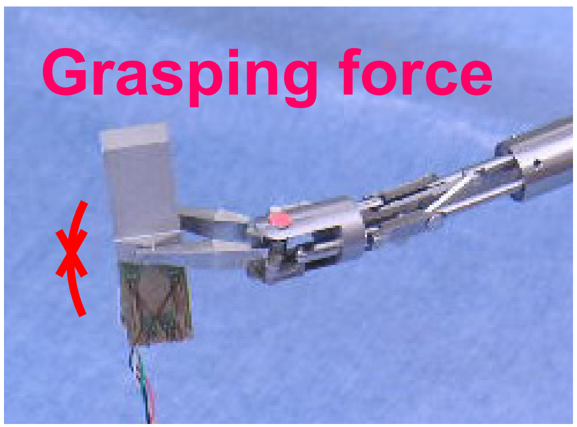


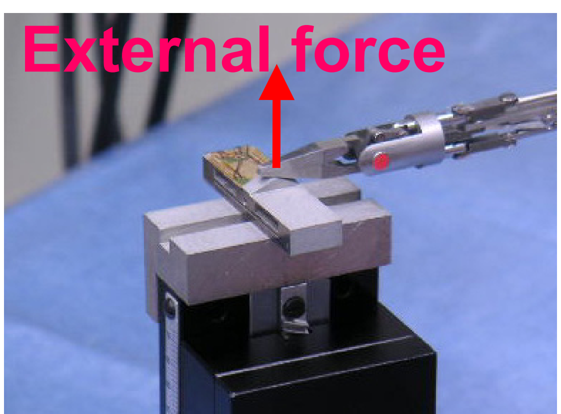
Sensorized forceps



Force measurement experiment

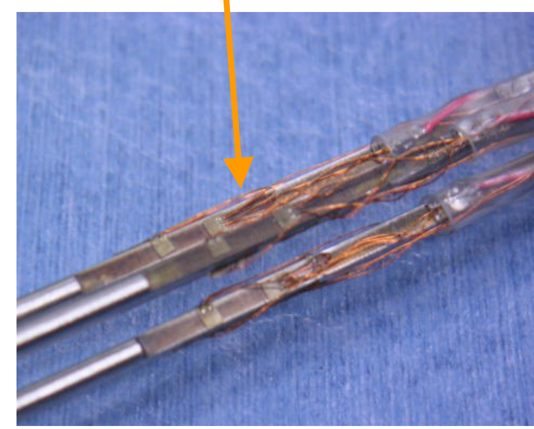
Actual grasping and external force were measured.

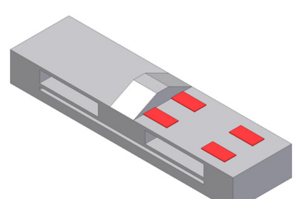




Compared

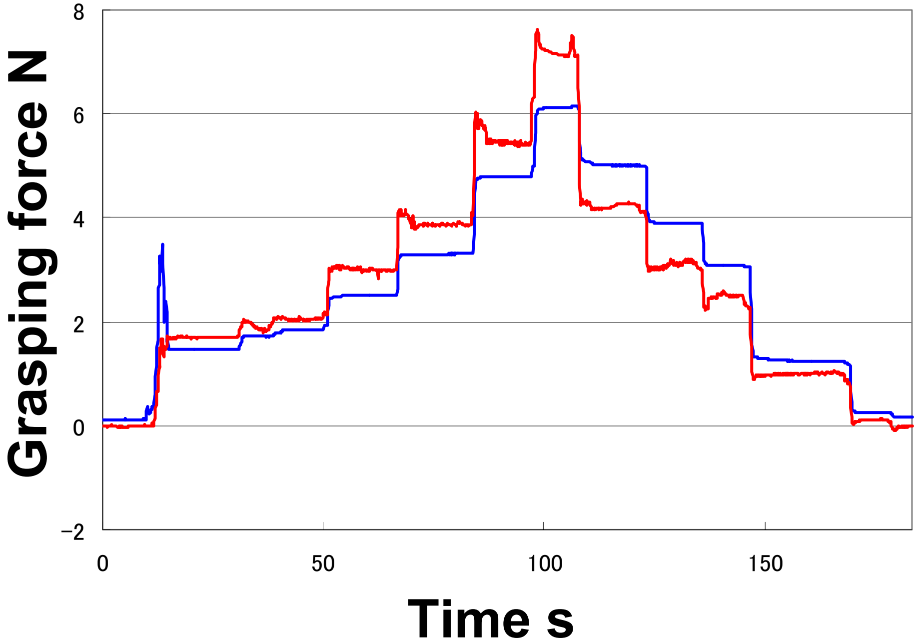
Calculate the grasping and external force using the force information acting on the driving links.





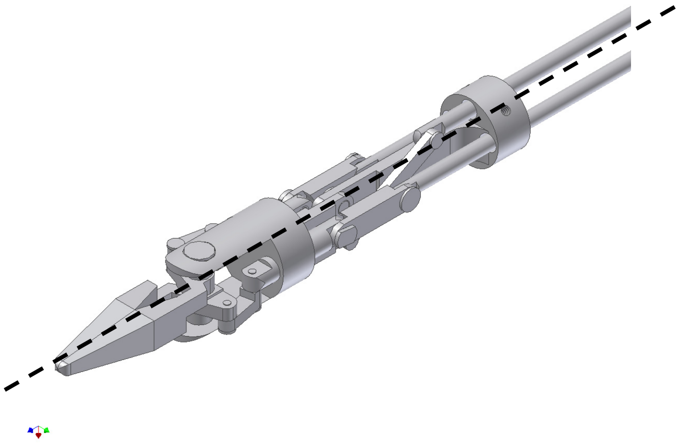
Force sensor:
Rated value: 20[N]
Resolutions: 0.01[N]

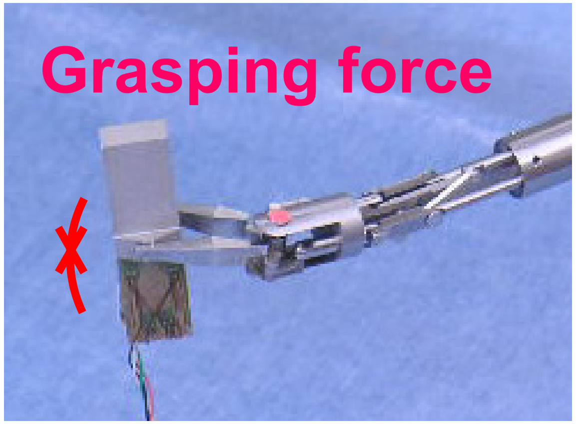
Measurement of the grasping force (1)



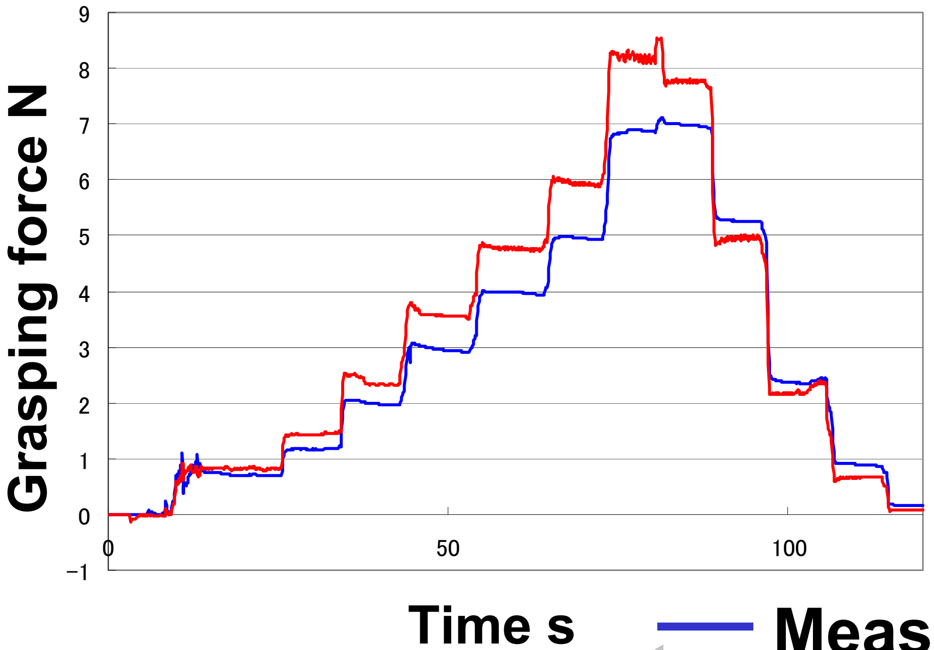
Measured grasping force
Calculated grasping force

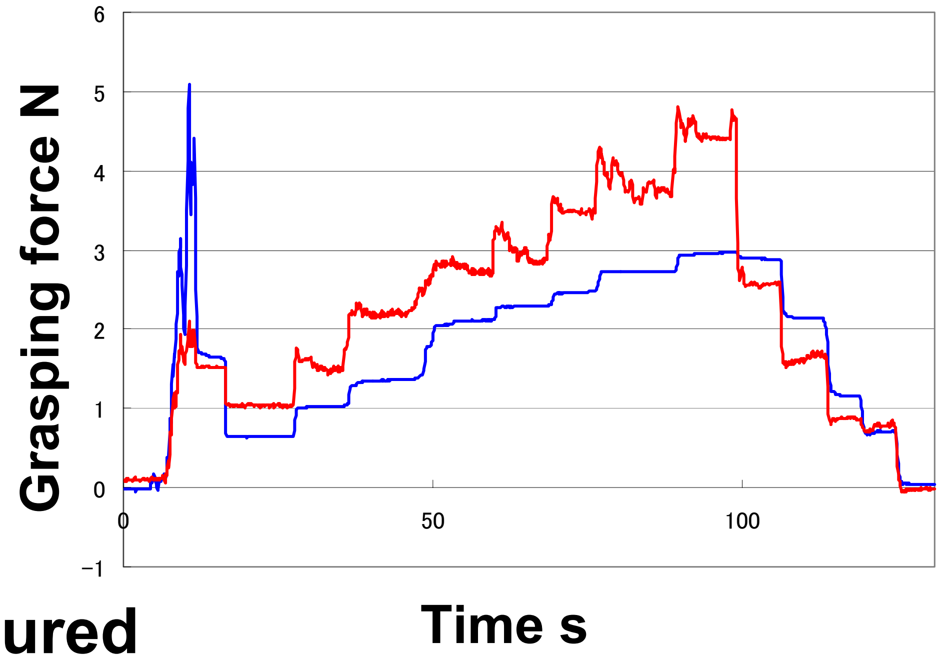
Without bending





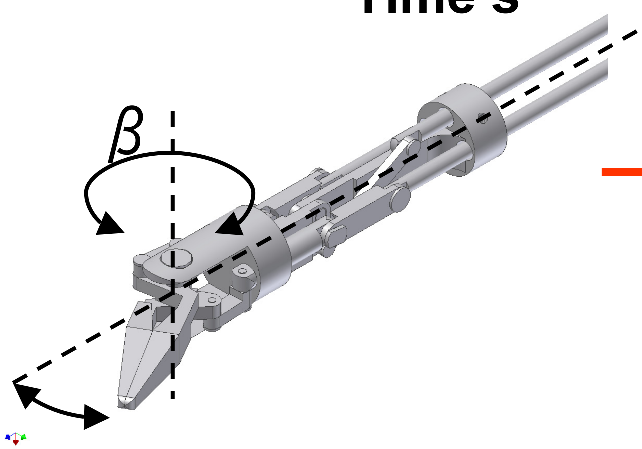
Measurement of the grasping force (2)



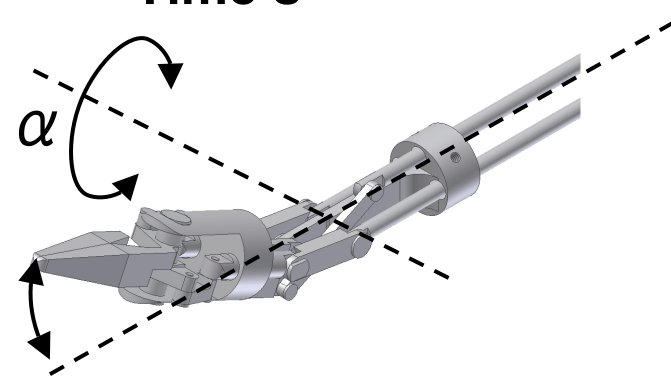


Measured grasping force

Calculated grasping force

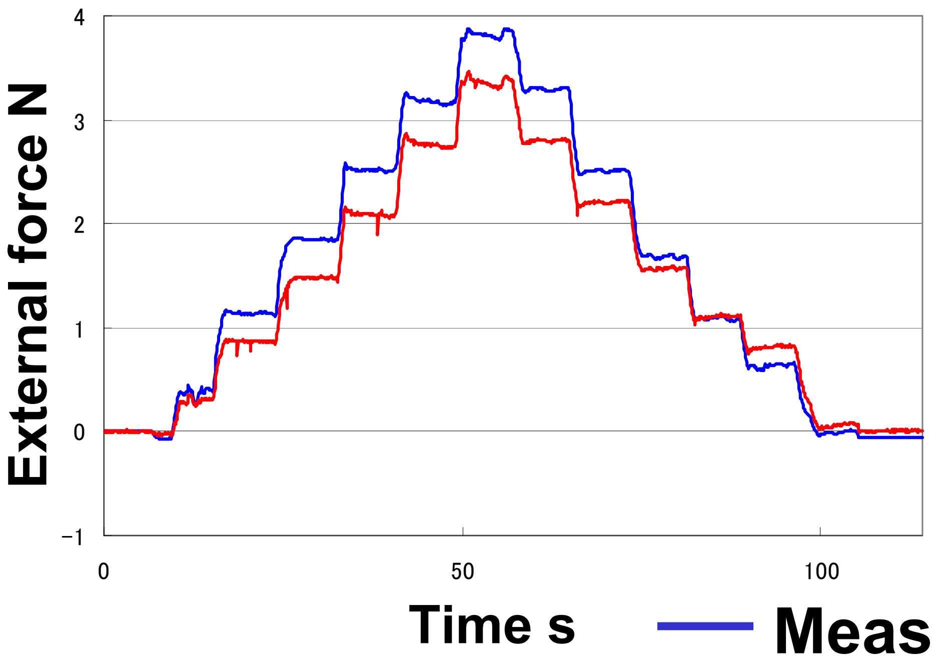


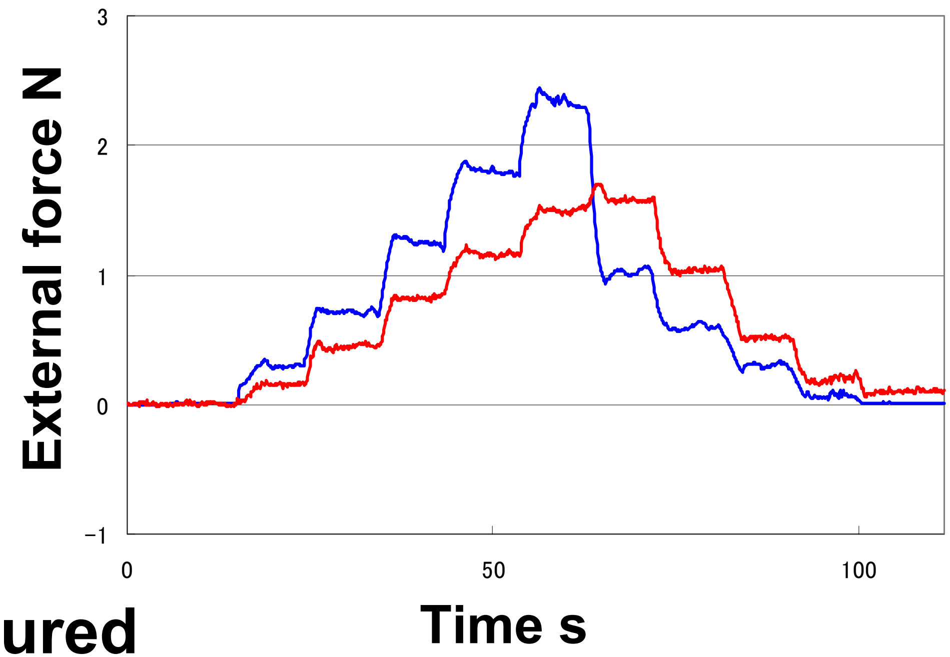
With bending: β =30 [deg]



With bending: α =25 [deg]

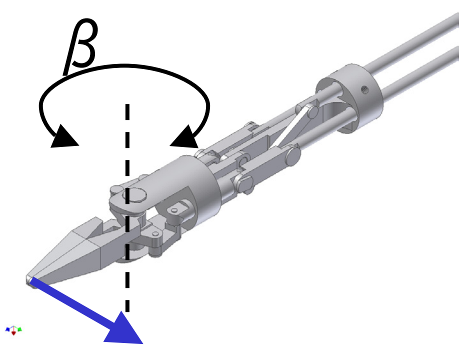
Measurement of the external force (1)



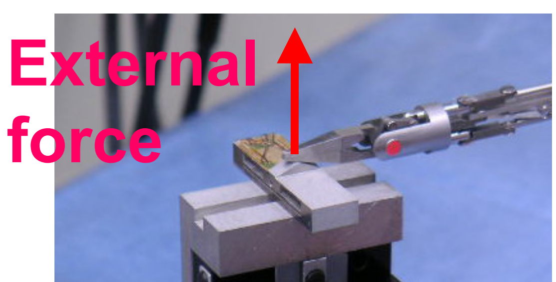


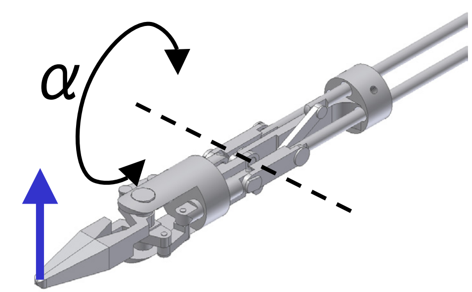
Measured external force

Calculated external force



External force F_β





External force F_α

Discussions (1)

Grasping force

- Error direction varies depending on the grasping force direction whether it is increasing or decreasing.
  → The direction of friction force varies at the sliding part.

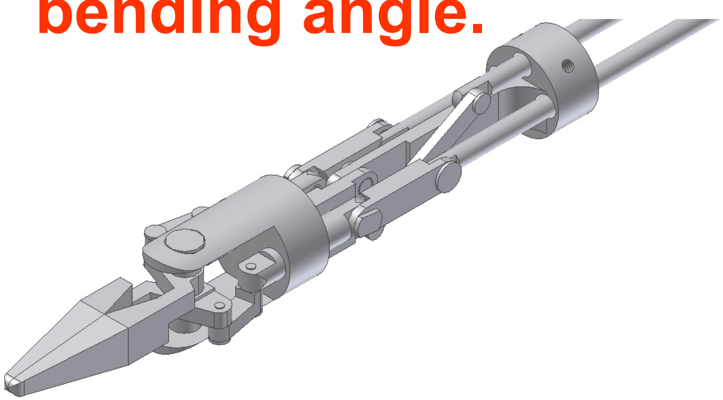
  While increasing the grasping force

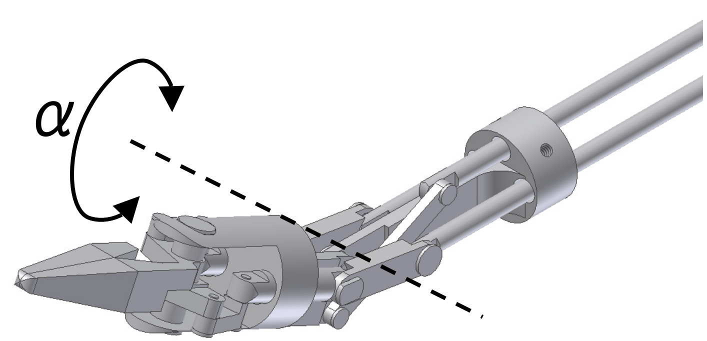
  (Calculated grasping force) = (Measured force) + (Friction force)

  While decreasing the grasping force

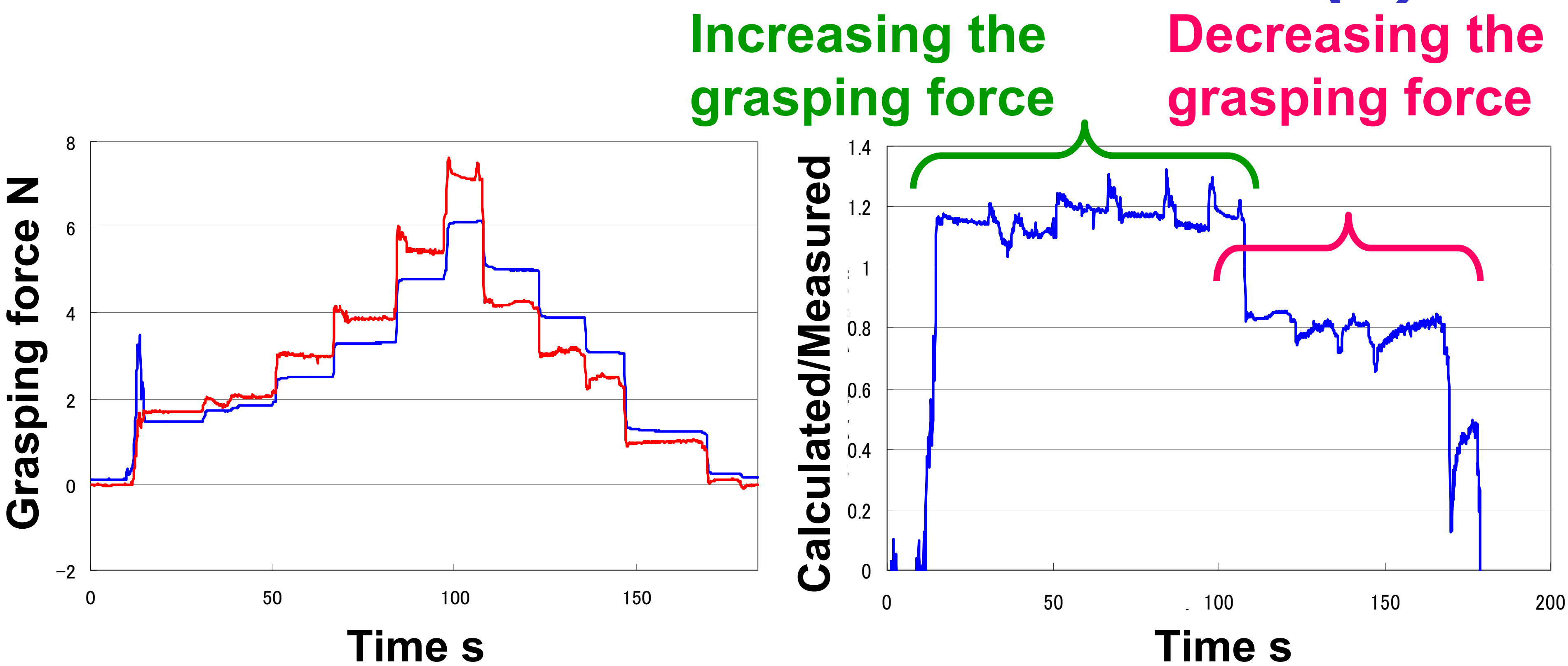
  (Calculated grasping force) = (Measured force) – (Friction force)

- Error value varies depending on the posture.
  → Friction condition varies depending on the bending angle.





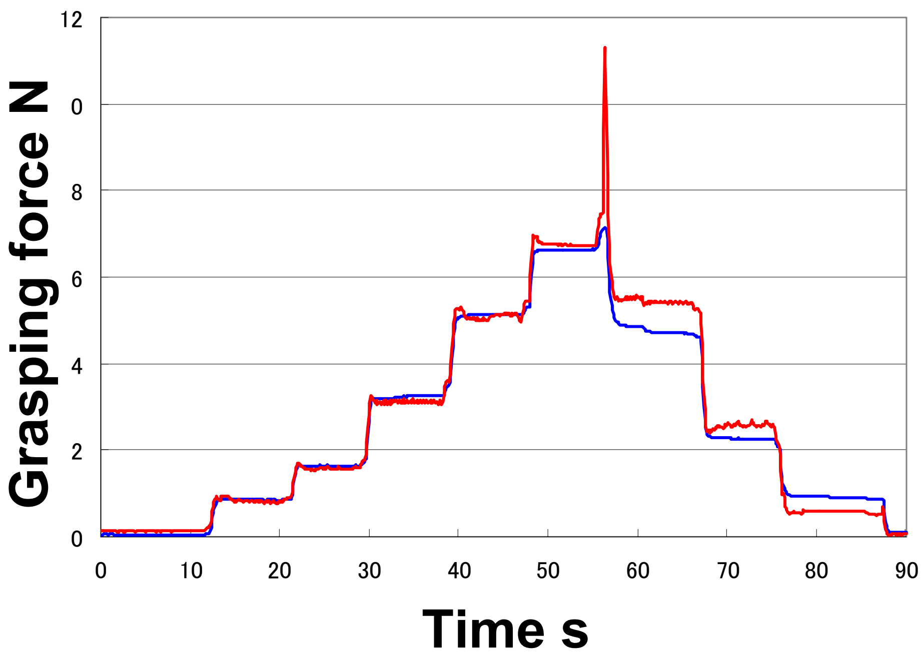
Discussions (2)

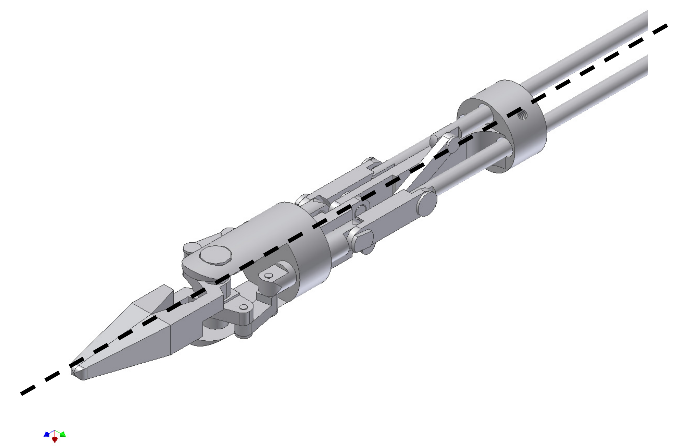


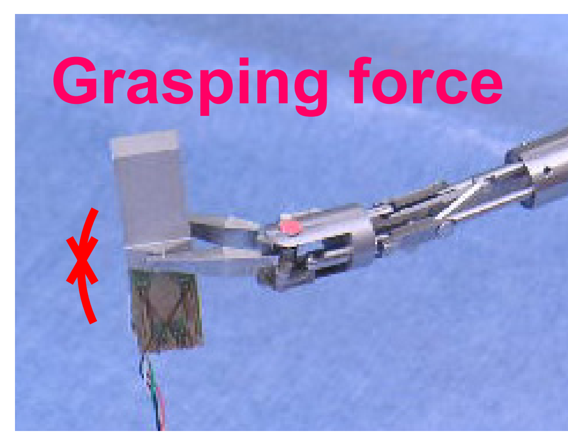
The ratio between the calculated and the measured force was obtained.

The ratio is almost constant while increasing and decreasing the grasping force.

Error compensation







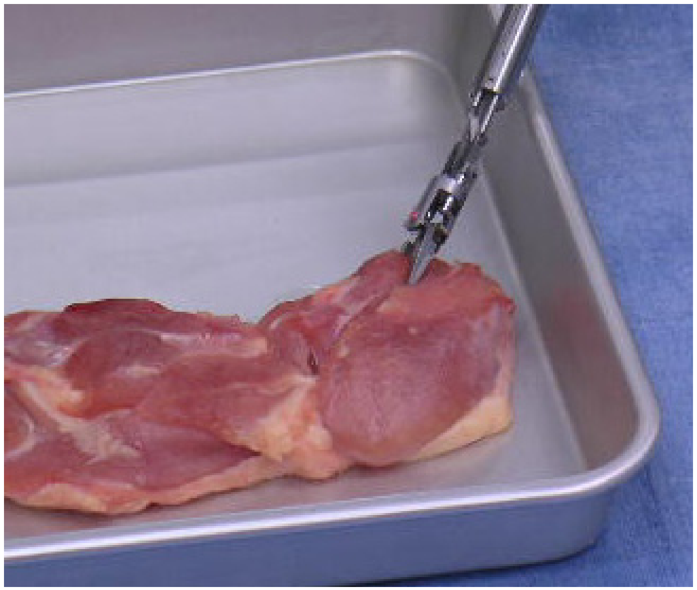
Measured grasping force

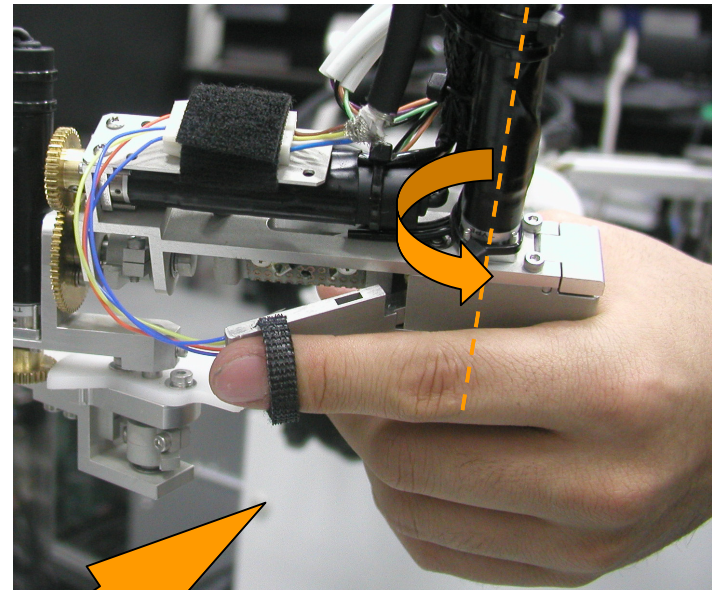
Calculated grasping force with error compensation

Friction force is considered.

Force information presentation

DC motor

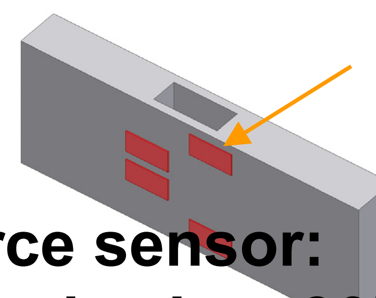




Grasp an object using a slave manipulator

Detect the grasping force

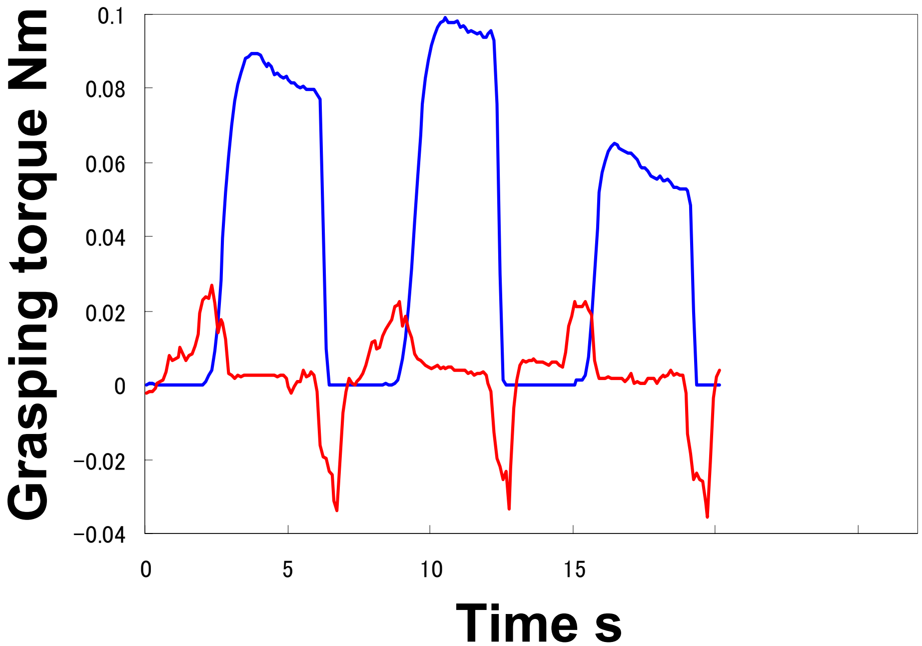
Force presentation



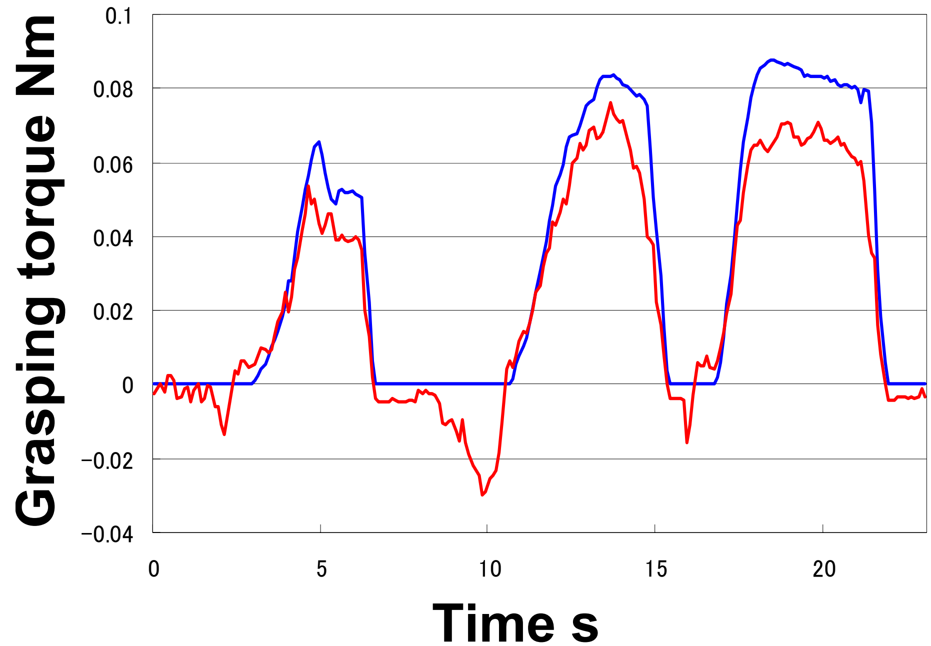
Strain gauges

Force sensor:
Rated value: 30[N]
Resolutions: 0.015[N]

Force presentation



Without force feedback



With force feedback by force reflection type control

Grasping force at the slave manipulator

Grasping force at the master manipulator

Japan-Korea remote surgery experiment: March 2nd, 2005

Conclusions

1. **A link-driven, multiple d.o.f. forceps for minimally invasive surgery has been developed. The design solved the cable cutting problem.**
2. **Force sensing method for the link driven type multiple d.o.f. forceps was developed.**
3. **An augmented force presentation controller was proposed. The load applied to a soft tissue was reduced approximately 30% compared with the conventional control method.**