Development of Autonomous Cable Inspection Robot for Nuclear Power Plant

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Abstract—The cables in a nuclear power plant are designed to be used for about 40 years in safe operation environment. However, the heat and radiation in the nuclear power plant causes the rapid performance deterioration of cables in nuclear vessels and heat exchangers, which requires cable lifetime estimation. The most accurate method of estimating the cable lifetime is to evaluate the cables in a laboratory. However, removing cables while the plant is operating is not allowed because of its safety and cost. In this paper, a robot system to estimate the cable lifetime in nuclear power plants is developed and tested. The developed robot system can calculate a modulus value to estimate the cable lifetime even when the nuclear power plant is in operation.

Keywords—Autonomous robot, Cable Inspection, Indenter, Nuclear Power Plant

I. INTRODUCTION

FOR the extended operation of a nuclear power plant after 40 years lifetime, the durability of its cables should be proven by showing that they are available more than 10 years in lifetime[1-3]. For this purpose, diagnosing the condition of the cables in the nuclear plant is an essential work. However, the removal and evaluation of the cables from the nuclear power plant cost as much as the purchase price of the cables. Moreover, such works are quite difficult to be completed during its overhaul period.

The deterioration of the cables is usually caused by temperature, humidity, chemicals and radiation. When the cables are exposed to 10˚C above a usual environment, the lifetimes of the cables are reduced by half. Chemicals can harden the cables, even if not causing fatal damage on the cables. In the case of radiation, it does not deteriorate the cable as much as temperature, but hastens cable weakening[4-7].

The cables in a nuclear power plant vessel are generally exposed to a certain amount of emission. If their exposure time to radiation is getting increase, their insulation resistance and tensile strength gradually decrease. This phenomenon reduces not only the reliability of the cables, but also the security of the nuclear power plant. For those reasons, the necessity of inspecting the cables has been increased.

To meet such demands, several methods have been applied to inspect the weakening degree of the cables. One commonly used method is cable aging estimation by dielectric strength. Because the dielectric strength is decayed as time passes, the method can be used to obtain the index of cable aging. One other way to estimate cable deterioration is measuring residual antioxidants in the cables. This method has a small dispersion error, because, in general, the chemical reaction occurs gradually over the cables.

The lifetime estimation using the modulus parameter on a cable is a non-destructive method. The modulus parameter can be calculated from the indention depth by force applied on the surface of the cable. This method does not take long time to perform the test. The test tool-kit is easy to develop and handle, and the estimated lifetime of the cable is given just after the test.

Though many diagnostic studies have been performed on non-destructive techniques, however, the studies were usually focused on improving measurement accuracy, not on a stochastic method by using various sampled data.
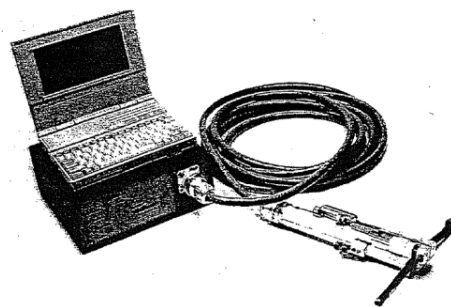

Fig. 1 Cable indenter developed by EPRI

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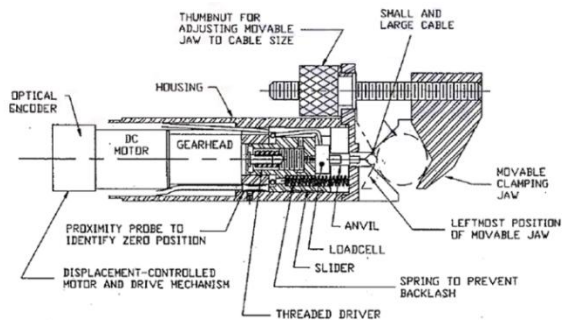International Journal of Mechanical and Mechatronics Engineering
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Fig. 2 Detailed schematic of cable indenter

EPRI (Electric Power Research Institute) in the United States through OGDEN Corp has developed a product called "Cable indenter aging monitor[8,9]", and announced the result of the study called "Evaluation of cable polymer aging through indenter testing of in-plant and Laboratory-Aged specimens". It is known that a portable cable degradation diagnostic system has been also developed in Canada and applied to its nuclear power plants, but its details are not known. The nuclear power plants in Hungary and Europe are also planning the development of such a diagnosis system.

Fig. 3 shows the cable indenter developed by KEPRI (Korea Electric Power Research Institute) in 1999. This cable inspection tool is a kind of handheld device for inspecting cable deterioration and its inspection results are received by a PDA. However, the developed system sometimes shows some error. The measured data are different depending on the probe positions on the multi core cables, cable roughness and human operator's proficiency, as shown in Fig. 3 and Fig. 4.

To solve this problem, we developed a new inspection robot system for the diagnosis of cable degradation that uses cable clamps and probes to improve its diagnostic accuracy. This robot can automatically inspect various types of cables within a short time with high accuracy and repeatability. Through experiments, we confirmed its effectiveness.

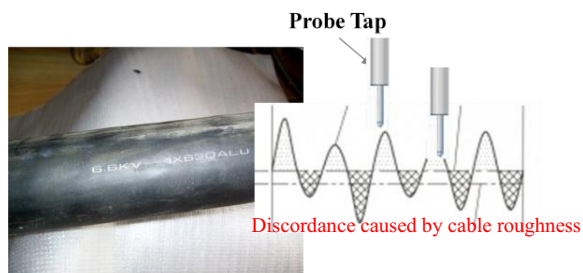Fig. 3 Cable indenter by KEPRI and its occurred discordance

Fig. 4 Discordance caused by cable roughness

II. DEVELOPMENT OF CABLE INDENTER ROBOT

A. Entire Robot System

The key issue of developing cable indenter robot is "Design a light and small robot which is able to inspect automatically stiffness of the object cable". Based on this design issue, developed robot consists of three parts. The mechanical part contains inspection sensors and mobile parts. The master robot controller rules motor drive systems and measuring mechanism. The remote controller receives acquired data from master robot controller and displays the data as a graph. The remote controller also transmits robot command to the robot master controller to control robot. To minimize the robot, the master controller is placed out of the mobile robot system. To make the robot lighter, the robot system is powered by line instead of using batteries. The master robot controller communicates with the remote controller via USB. Fig. 5 shows the entire diagram of the robot system.
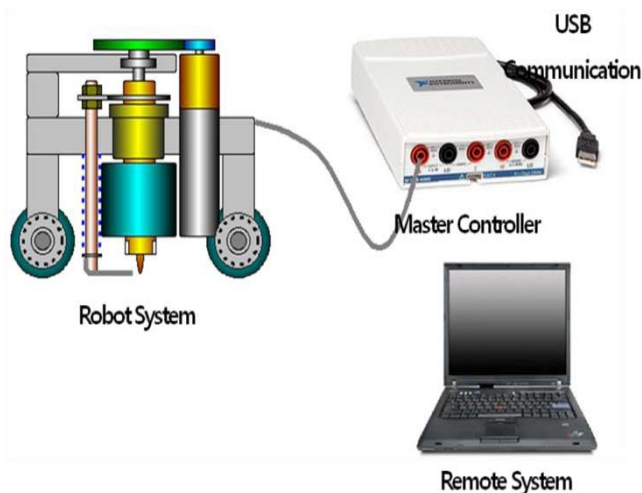

Fig. 5 Schematic Diagram of System

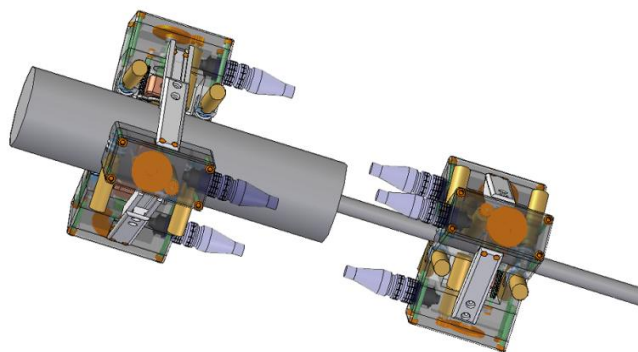### B. The Mechanical Part of Robot System

Fig. 6 Designed Mechanical Part of Robot System

Fig. 6 shows mechanical part of robot system. The cable stiffness measurement robot is wheel type robot. The mechanical part of robot system linked with three robot blocks. Each robot block contains actuation module, inspection module and connection module.

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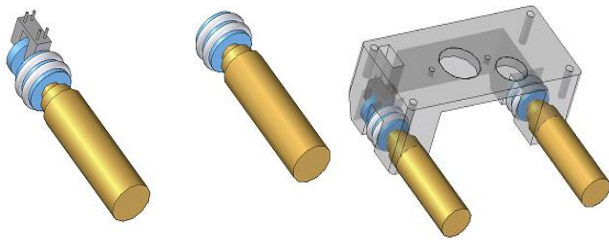International Journal of Mechanical and Mechatronics Engineering
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Fig. 7 Design of Actuation Module

The actuation module consists of wheels, DC motor and photo micro switch. The small DC motor drives robot wheel which allows the robot system to move along the power line used in nuclear power plant. The distance can be calculated by counting photo micro pulse. The actuation module is shown in Fig. 7.
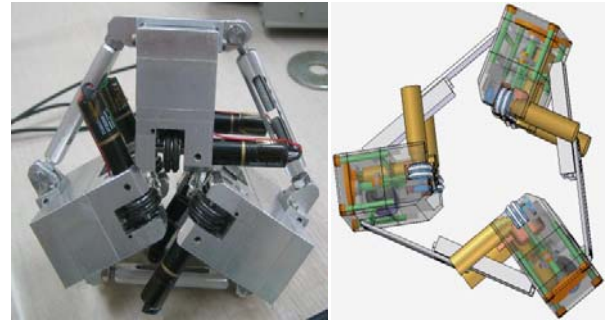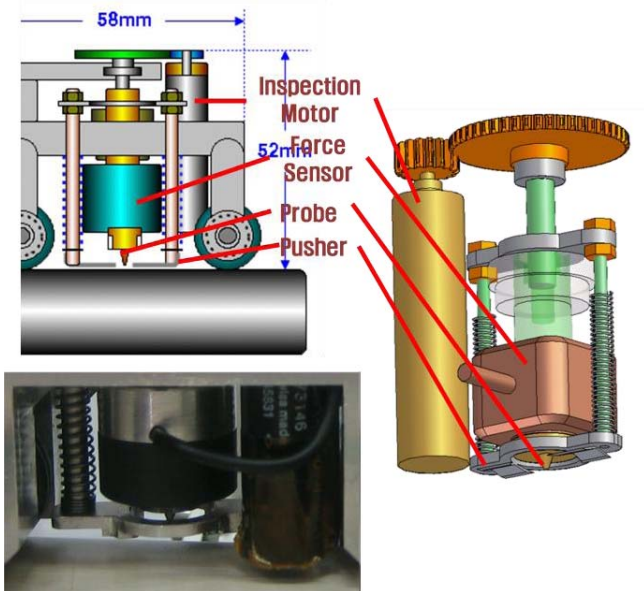

Fig. 8 Design of Inspection Module

Fig. 8 shows inspection module. The concept of inspection module is simply measuring arbitrary force which is working on the probe during the probe pointing a cable. The probe should move down to a cable perpendicularly in order to measure vertical force of an object cable while the probe pokes. The Pusher and spring flattens the cable surface so that the probe remains at right angles with the cable.

Inspection module consists of DC geared motor with encoder, spur gear driven by DC motor, Ball-Nut which converts rotary motion into vertical motion, force sensor attached on the end of the Ball-Nut and probe.

While the robot moving, the probe should be mounted at the top position of the inspection module so that the probe does not disturb robot moving. To set reference position of the probe, a micro switch is installed at the top of the inspection module.

Cable inspection robot installs around the object cable. Three inspection modules are used to measure the force on the probes. The degree of coupling is 120˚. This symmetric structure makes the robot acquires uniform force information.
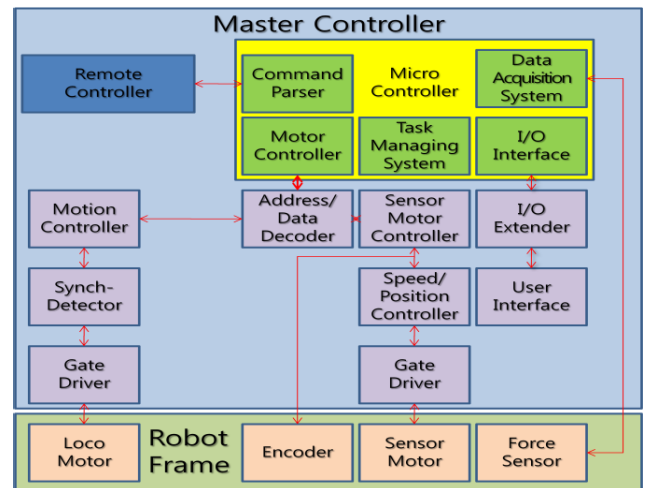

Fig. 9 Connected Robot Frame

Fig. 10 Block Diagram of Electric Parts

C. Electrical Part of Robot System

The robot system contains several motors and sensors, indeed one needed to drive those actuators and sensors. Master controller contains DC motor controller which varies sensor motor speed and position, I/O Interface which the user can give command to the robot system which acquires analog data from force sensors mounted on the robot. The task managing system executes appropriate task on time. Because the control system should govern three DC motor controllers, which is specialized DC motor controller DSP (LM629), in the same time, I/Os of the micro-controller have to be extended. Extended I/O system is also available for MMI (Man-Machine-Interface). Fig. 10 shows block diagram of electric parts

D. Sensors

Various sensors are used to control the robot and measure force information. Photo sensors and micro switches are used to control robot procedure. Especially, the force sensor on the inspection robot is a key component in performance determine. Typically, dynamic force sensors to measure small force have been developed in various dimension, but not in static force sensors for small force. Even the static force sensors we found were not suitable for the robot, because the structure was not matched with probe and Ball-Nut. For this reason, KEPRI developed a small size force sensor using Honeywell piezo resistive sensor. Table I shows Specifications of force sensor.

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TABLE I
SPECIFICATION OF DEVELOPED FORCE SENSOR

Model/ Manufacturer	FSS1500NSB/ Honeywell	MCSR-2L/ Toyo
Sensitivity	0.12mv/g typ.	0.12mv/g typ.
Operating Force	0 to 1500g	0 to 2040g
Supply Voltage	5.0 Vdc	5.0 Vdc
Null Offset	± 15mv	± 10%
Linearity	± 1.5% Span	± 1.0% Span
Null Shift over Temp.	± 0.5 mV typ. (25˚C)	± 2 % Span (10˚C)
Sensitivity Shift	± 5.5 % Span typ. (25˚C)	± 1 % Span (10˚C)
Input Resistance	5.0 KΩ	350±10Ω
Output resistance	5.0 KΩ	350±10Ω
Over force	4,500g	2,000g
Deflection at rate load	0.03mm	0.01mm
Dimension		

E. Robot Control Procedure

Developed robot system controls 3 moving motors, photo-interrupts to detect robot movement, inspection motors, encoders, probes and micro switches to detect probe position. After power-on, the robot follows listed order to initialize the robot system.

i. After the power is in the robot, the robot drives loco motor.
ii. After detecting photo-interrupt signal on loco motor, the robot stop driving loco-motor.
iii. Sensor motor drives probe to mount the sensor on the top position of the inspection module. The motor stops driving when the probe touches the micro switch on the top of the inspection module.

The robot system is waiting for user command to inspect cable deterioration. When the robot inspect a cable the robot system follows listed order

i. Drive loco motor to move along a cable.
ii. The loco motor stops when the microprocessor detects photo-interrupt signal on loco motor.
iii. After stop moving loco motor, the robot drives inspection motor down with pre-determined acceleration and speed.
iv. When the measured force exceeds 1gf than usual force, the controller stop moving the inspection motor.
v. The micro controller assumes the probe touches cable surface since the measured force increased a little bit, and the micro-controller measures force reference value to inspect cable modulus value.
vi. The robot controller drives the inspection motor up 0.1mm to speed up measurement probe when the probe contacts with cable surface while the probe inspecting.

vii. The controller drives probe down to the cable center with a preset speed and acceleration.
viii. The robot controller transmits measured force and distance data to remote controller every 20ms while inspecting.
ix. When the measured force exceeds a set value, the robot stop moving probe.
x. The robot controller waits for finishing the inspection task on other inspection modules.
xi. When other inspection modules finish inspection task, the controller retracts probe on each inspection module to the top position in order to move other position on the cable
xii. Execute step *i* again.

III. EXPERIMENT AND RESULT

After building the robot system, the robot has been applied to test cable which was sampled from nuclear power plant. First, we installed and operated the robot to verify that the joints works properly while the task. Second, we checked force sensor output during the robot performs cable inspection task. Fig. 11 shows robot installed, probe position while inspecting and force sensor output.

(a) Installed robot system to inspect   *(b) Performing inspection*

(c) Finished inspection task   *(d) Output signal of force sensor*
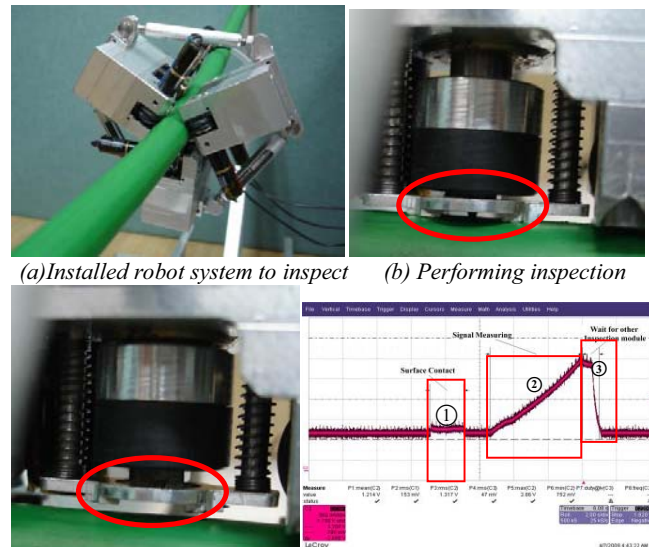Fig. 11 Indoor experiment of cable inspection robot

Fig. 11(a) shows the installed robot system, the robot should be remained in 120° even the robot rotates. The robot can be applied on a various size of cables by fitting turn-buckle between inspection modules. Fig. 11(d) shows output signal of force sensor during inspection. Fig. 11(d)① shows surface contact of inspection probe. Shown as Fig. 11(d)①, the output value of force is slightly increased. Fig. 11(d)② shows force increase while inspecting cable. Fig. 11(b) shows the probe position during inspection. The robot is waiting for other inspection modules to finish the task and retracts the probe on each inspection module, Fig. 11(c)(d)③.
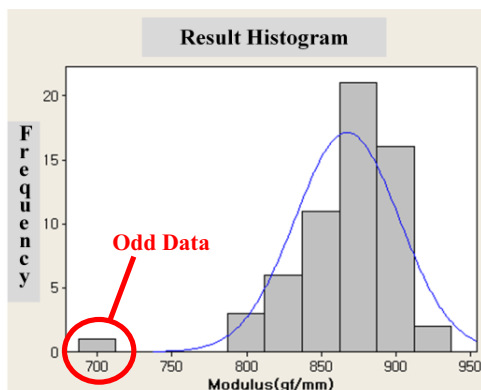
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Fig. 12 Indoor experiment of cable inspection robot

TABLE II
CALCULATED INDENTER MODULUS OF SAMPLE CABLE

Module 1	Module 2	Module 3
921.69	858.15	896.09
842.08	881.34	888.83
865.03	844.78	882.52
914.09	876.04	902.63
854.51	851.48	901.74
824.83	847.27	874.93
824.83	828.10	875.61
865.87	825.02	860.32
873.15	806.92	802.03
873.15	835.16	889.44
865.63	866.31	882.10
880.58	890.57	888.76
895.41	888.31	908.01
896.16	912.22	899.32
884.22	879.22	861.24
910.30	885.93	852.64
843.66	896.31	811.56
881.09	883.89	871.80
878.55	862.46	709.39
826.12	863.10	902.80

Using the developed robot, KEPRI measured modulus (gf/mm) values. Table II and Fig. 12 show the measured modulus values and the processed data on the testing cable.

IV. CONCLUSION

In this paper, a novel cable inspection robot system has been developed for nuclear power plants. The developed system autonomously measures force data in the various positions of cables. The acquired data are used to evaluate the indent modulus by which the cable lifetime can be estimated. The developed robot system is easy to carry and apply in the nuclear power site. A small precise force sensor and a cable pusher are applied to improve the accuracy of the robot system.

However, the measured data may include some odd data that should be excluded to calculate indent modulus. To solve this problem, we need more study on statistics and data sampling techniques. In addition, the cable lifetime should be estimated using Arrhenius equation and the indent modulus[10].

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